NAS8-35596

ABSTRACT

The purpose of the study was to demonstrate the capability of predicting two-dimensional, compressible and reacting flow in the combustion chamber and nozzle of the Space Shuttle Main Engine (SSME). CHAM's general purpose Computational Fluid Dyanmics (CFD) code, PHOENICS, has been used. A non-orthogonal body fitted coordinate system has been used to represent the nozzle geometry. The Navier-Stokes equations are solved for the entire nozzle with the $k\sim\varepsilon$ turbulence model. The wall boundary conditions have been calculated based on the wall functions which account for pressure gradients.

Results of the demonstration test case reveal all expected features of the transonic nozzle flows.

Of particular interest is the location of an internal shock, and regions of highest temperature gradients. Calculated performance (global) parameters such as thrust chamber flow rate, thrust and specific impulse are also in reasonable agreement with available data.

Recommendations are made for further improvements in the physical models, as well as for the use of numerical model at NASA MSFC.

CONTENTS

PREFACE

CHAM of North America Incorporated has performed the present study for the NASA Marshall Space Flight Center under the contract NAS8-35559. This is the final report for the contract.

The authors wish to thank the following individuals for their contributions to the project.

- Mr. Klaus Gross (NASA MSFC) for technical guidance;
- John Edwards (CHAM UK) and Fritz Owens (CHAM NA) for support in the initial development of the model;
- Jack Keck (CHAM NA) for support in contractual arrangements; and
- Kelli King and Janet Siersma, for the typescripts of the report.

Section 1

INTRODUCTION

1.1 Thrust Chamber Simulation Status

The thrust chamber of the Space Shuttle Main Engine (SSME) consists of main combustion chamber with the injector plate assembly and the attached nozzle expansion section. Figure 1.1. presents the SSME combustion chamber and the transonic flow nozzle. Figure 1.2 presents the SSME main injector assembly. The reactants: preburner combustion products, liquid oxygen and some liquid hydrogen, are injected to the thrust chamber through a main injector plate with 525 "concentric orifice" injectors (diffusive type burners) and 75 "baffle elements" (premixed type burners). Propellants injected to the chamber are atomized, vaporized, mixed and combusted within the combustor volume. The reaction products are expanded through a subsonic/supersonic nozzle. The chemical kinetics of combustion reactions extends from the flame front to the expansion region.

Proper design of a thrust chamber requires detailed knowledge of the flow pattern, temperature, concentration and pressure profiles as well as global parameters such as specific impulse, thrust, and wall heat flux.

A mathematical model can provide such information in a cost effective manner and can aid in analyzing several designs and operational problems, for example:

1. prevention of hot spots along the chamber wall and injector;
2. prediction of pressure distribution and flow pattern (shock waves, boundary layer buildup and/or blowdown and/or creation of recirculation or stagnation zones);
3. transient flow simulation (for start-up, shut-down and throttling situations); and
4. influence of injection nonuniformities on the fluid flow, heat transfer and combustion within the chamber.

Currently existing mathematical models for predicting the performance, propellant flow and combustion processes in rocket engines are identified in the "JANNAF

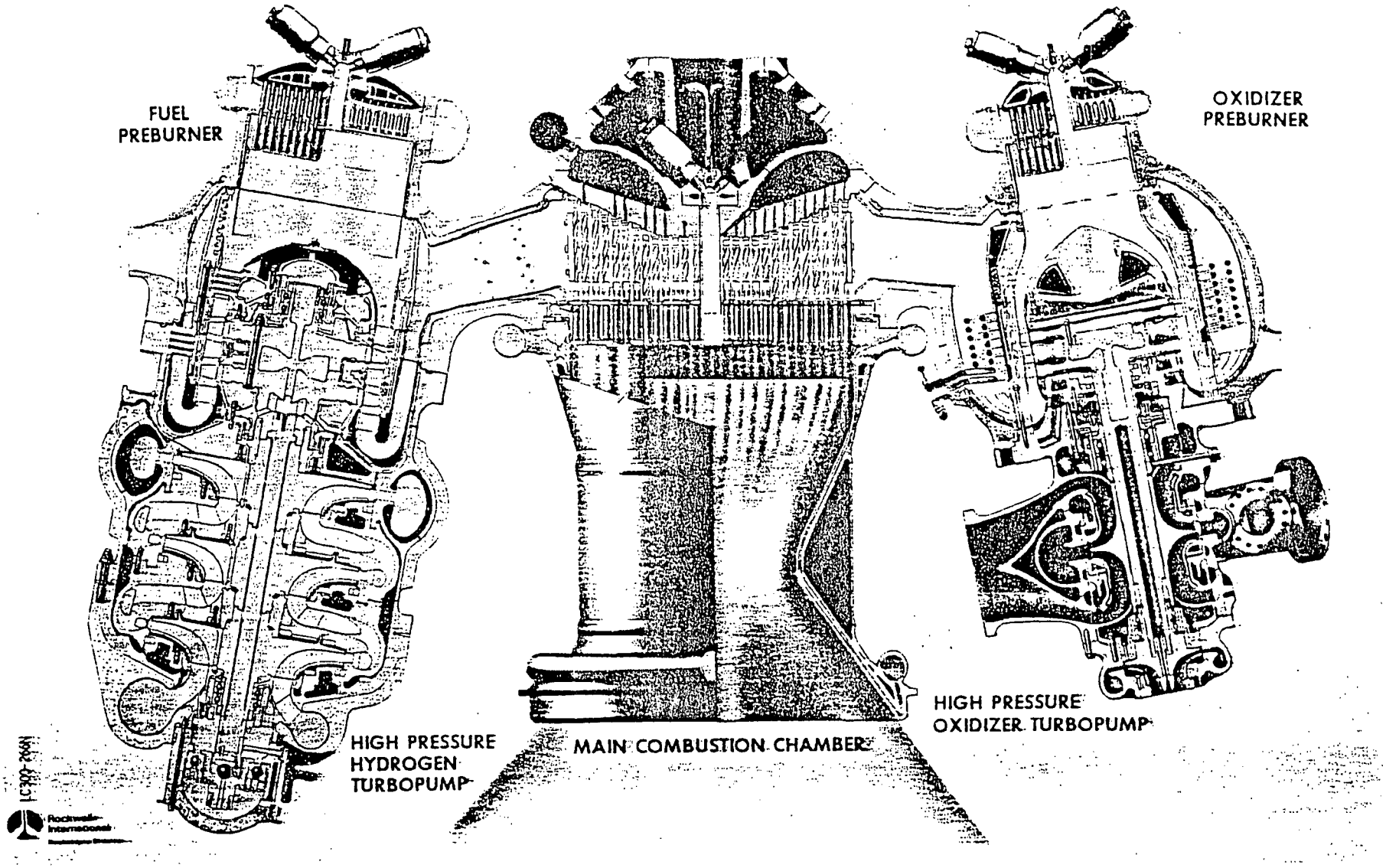

Figure 1.1 Illustration of the SSME Combustion Chamber

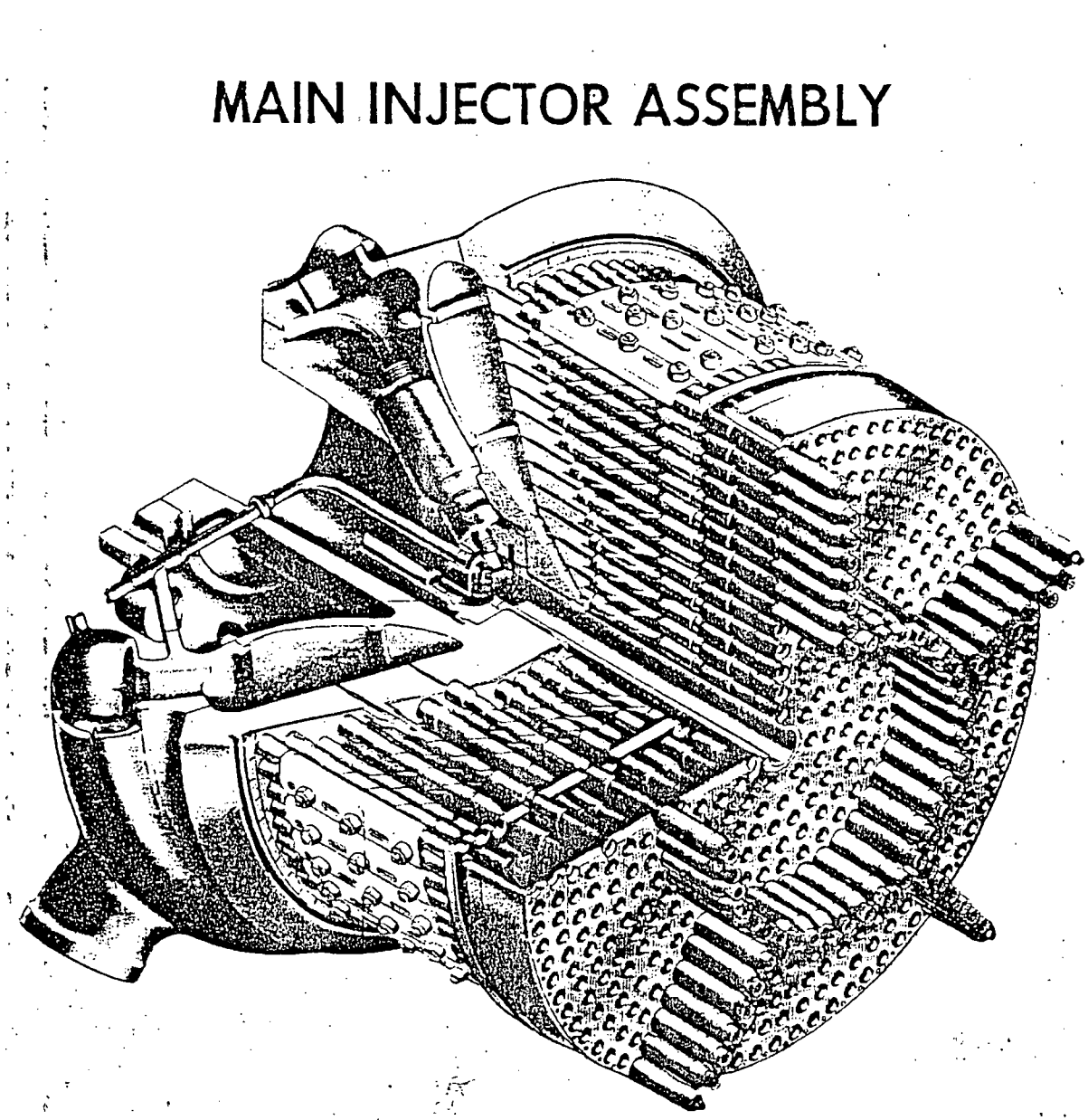

Figure 1.2 Illustration of the SSME Main Injector Assembly

Rigorous Analytical Procedure" (Reference 1). In this procedure the performance of the thrust chamber is based on the application of the following two computer codes:

TDK - "Two Dimensional Kinetics" (Reference 1) program for predicting the inviscid flow field using the method of characteristics with finite rate chemical kinetics, and

BLIMP - Boundary Layer Integral Matrix Procedure (Reference 2) for predicting viscous effects in the boundary layer zone near the chamber walls. The program solves parabolic equations for momentum, and energy equations, with an algebraic turbulence model. It assumes chemical equilibrium of combustion reactions.

The rigorous approach requires iterative calculations between these two programs in order to predict correct momentum and energy losses due to the interactions of inviscid flow and viscous boundary layer.

Recent progress in Computational Fluid Dynamics (CFD) has lead to more advanced procedures and computer codes which are capable of simulating flows with above mentioned features. These codes solve Navier-Stokes equations by iterative solution algorithms. Since these equations represent fluid flow fields in general, solutions may be obtained for many conditions that exceed the existing TDK/BLIMP capability which considers only axisymmetric thrust chambers with cone or common bell shaped nozzles.

Some future benefits from the advanced codes are:

- Calculation of the subsonic, transonic and supersonic flow field with the same analytical concept for viscous and inviscid conditions.
- Simulation of shock waves.
- Flow separation at the wall.
- Other than axisymmetric nozzles.
- Dual throat thrust chambers.
- Thrust chambers operating in wind tunnels or with ejector systems.
- Flow over gaps or around protrusions in the nozzle wall.
- Transient flow simulation for start-up, shut-down and throttling situations.

One such procedure has recently been applied to a three-dimensional, elliptic, two-phase flow problem to study the effects of rocket injector anomalies on wall heat transfer (Reference 3). Another example of new codes is CHAM's general purpose CFD code PHOENICS (Reference 4). PHOENICS has been applied to numerous diversified problems including several for NASA (References 5 to 8). Because of the flexibility of PHOENICS, and its current use at NASA MSFC for other projects, PHOENICS has been selected for the present study.

1.2 Project Objectives

The objective of this project was to demonstrate the suitability of PHOENICS (an existing general purpose multidimensional, elliptic, viscous flow and heat transfer computer code; Reference 9), for predicting flow with combustion in SSME thrust chamber.

Another important objective was to describe advantages and shortcomings of the proposed approach so as to assist NASA personnel in making comparisons between the CFD approach and the JANNAF procedure. Some of the pertinent questions are:

1. How much time is necessary to prepare the input data to the code?
2. What type of computer will execute the program efficiently? (Identify core requirement.)
3. What is the computer program execution time?
4. What is the accuracy of the analytical results?
5. What is the status of the existing code and what problems pose significant difficulties?

1.3 Outline of the Report

The next section (Section 2) provides a brief description of the salient features of PHOENICS. Details of the specified SSME nozzle test case, selected computational grid distribution and boundary conditions are specified in Section 3. Implementation of this case in PHOENICS is described in detail in Section 4.

Computed results and their discussion are presented in Section 5. Specific answers to the above mentioned questions are provided in Section 6. Conclusions and Recommendations are provided in Section 7. All references are listed in Section 8.

Section 2
DESCRIPTION OF THE PHOENICS CODE

2.1 General Information on PHOENICS

PHOENICS is a general purpose CFD code capable of solving transport equations in arbitary geometrical configurations. The name PHOENICS is an acronym: it stands for Parabolic, Hyperbolic Or Elliptic Numerical-Integration Code Series.

The code consists of three modules:

SATELLITE - for problem specifications;

GROUND - for incorporation of new physical models; and

EARTH - for solving the basic equations of fluid flow, heat and mass transfer.

The SATELLITE program prepares data files, and acts in accordance with the information provided. Figure 2.1 presents the flow chart of the operation of the PHOENICS. It can be seen that there is only one-way interaction between SATELLITE and EARTH, and a continous interaction between EARTH and GROUND. For a more detailed description of EARTH, SATELLITE and GROUND the "PHOENICS Users Manual" (Reference 9) is recommended.

Other salient features of the code are summarized below.

- GEOMETRY

  The code provides great flexibility in geometry and grid selection including:

  a) Body Fitted Coordinates (BFC) for representing complex domains with general nonorthogonal grid; and

  b) Porosity-Resistivity concept for representing blocked volumes, flow obstacles, perforated plates, etc.

Both cartesian and cylindrical polar coordinates can be used. The available geometrical options offer versatility of Finite-Element Methods (FEM) and simplicity of Finite Difference Methods (FDM). PHOENICS uses a Control Volume Method for discretization of the differential equations which, for regular geometries, is equivalent to FDM, and is briefly outlined in Section 2.3

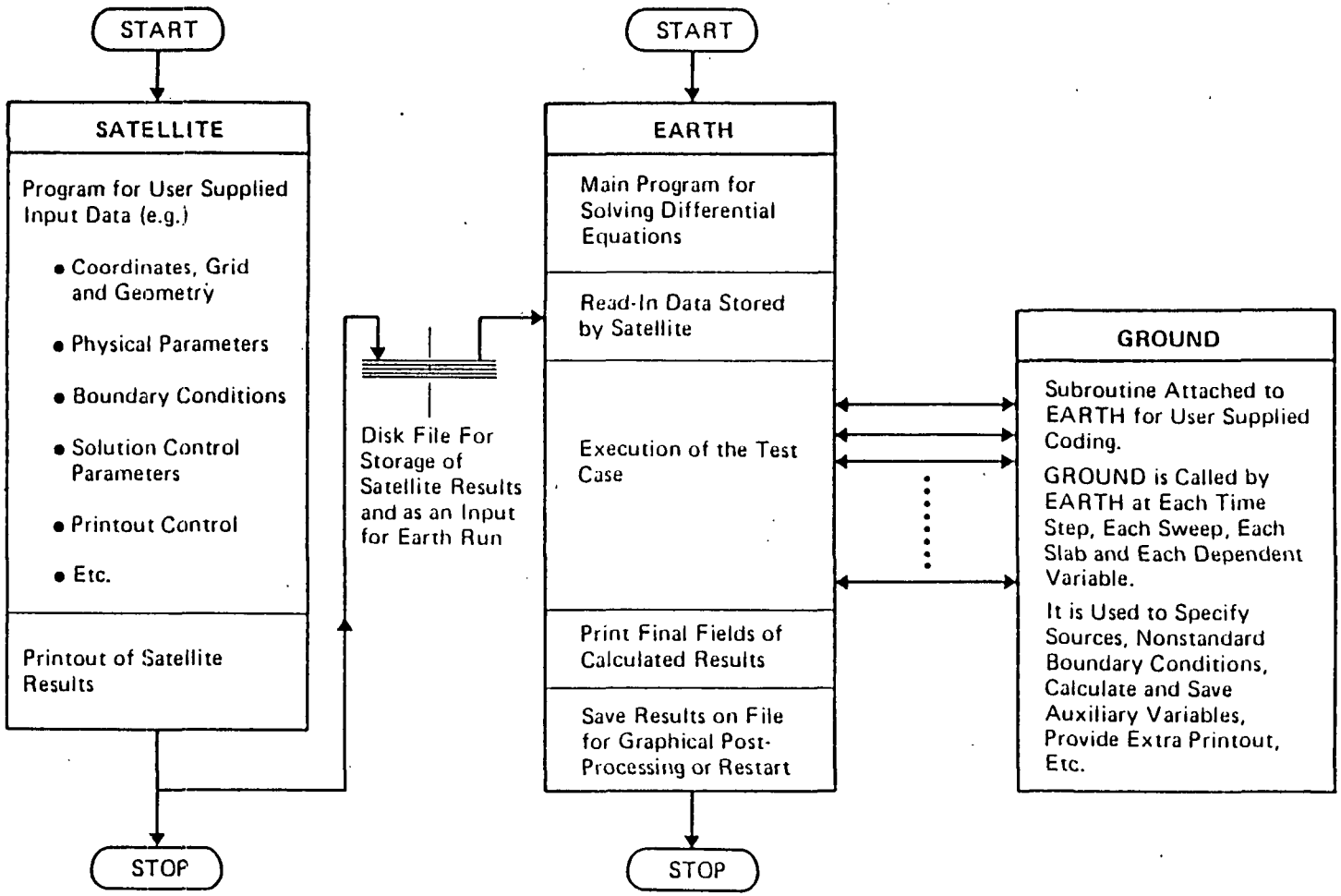

Figure 2.1 The Flow Diagram of PHOENICS Computer Program

It should be pointed out that the solution task in PHOENICS is similar to that in FDM as the coefficient matrices are positively defined and regularly diagonally dominant (in FEM they are sparse and not always diagonally dominant). Both storage and computational effort are significantly greater in Finite Element Method (FEM).

- PHYSICS

  PHOENICS can solve up to 25 dependent variables. The specified dependent variables are:

  - velocity components for each of two phases;
  - enthalpies, temperatures and pressures for both phases;
  - two-turbulence quantities;
  - four concentrations;
  - the volume fractions of the interpenetrating media;
  - three equations for radiation flux components; and
  - few user specified variables.

- NUMERICS

  Fully conservative and implicit formulations are used. As a result, there are no stability constraints, as commonly experienced in explicit and semi-explicit time marching methods. Equations are solved in "fully conservative" form ensuring both local (grid cell) and overall conservativion of all properties. This is difficult to accomplish in Finite Element Method or high order numerical methods.

- PORTABILITY

  The code is written in ANSI standard FORTRAN operational on a large variety of computers; from mainframes as CRAY to mini computers as Perkin-Elmer, VAX, etc. Efficient storage management ensures that the computer space is only used for those variables which are solved for, or reserved by the user, at locations equal to the grid cell number. No change in COMMON or DIMENSION is required. The code dynamically

reserves the storage from one run to another. PHOENICS is user-oriented, well documented and verified for several problems. There are several "PHOENICS Demonstration Reports" (PDR's), from which potential users can benefit by adding more complex physics or geometry.

2.2 Basic Equations

PHOENICS solves the discretized versions of the basic differential equations which express the physical laws of "conservation" of mass, momentum and energy. The code has provisions of simulating both single and two-phase flows. In the two-phase flow mode, for a general conserved property, ϕ, the transport equation is:

$$\frac{\partial}{\partial t}(r\rho\phi) + \text{div}\,(r\rho\vec{V}\phi - r\Gamma_\phi \text{grad}\,\phi) = \dot{m} + rS_\phi \qquad (2.1)$$

where ϕ stands for any of the dependent variables, r is the volume fraction of selected phases, ρ and Γ_ϕ are density and exchange coefficient; $\vec{V}$ is the velocity vector, $\dot{m}$ is the interphase mass transfer rate (e.g. evaporation rate) and S_ϕ represents the source term. Equations for the various quantities differ primarly in the way in which the source terms and transport (exchange) coefficients are calculated.

The above equation takes the special (simplified) form for the continuity equation:

$$\frac{\partial}{\partial t}(r\rho) + \text{div}\,(r\rho\vec{V}) = \dot{m} \qquad (2.2)$$

The momentum equations are solved in each coordinate direction for each phase.

For a single phase flow, in equation 2.1 and 2.2, r becomes unity and $\dot{m}$ becomes zero.

A two equation $k\sim\varepsilon$ turbulence model is employed to calculate the turbulent exchange coefficients.

Details of the $k\sim\varepsilon$ model can be found in References 10 and 11.

2.3 Outline of Solution Procedure

In Body Fitted Coordinates (BFC) the general finite difference equations are devised without any restrictions on the type of coordinate transformations, through the integration over a control volume. The resulting finite difference expressions are in conservative forms based on the staggered grid systems.

The details of discretization in BFC are tedious and would require extensive vector algebra introduction and will not be derived here. However, most of the fundamental ideas stem from the procedure based on Cartesian coordinates in the original work by Patankar and Spalding (Reference 12, see also Reference 13).

The resulting algebraic equations obtained from integration of differential equations over the control volume are of the form:

$$a_p\phi_p = \Sigma a_d\phi_d + S_\phi \qquad d = E, W, N, S, H \text{ and } L \qquad (2.3)$$

where subscripts P, N, W, W etc. denote the grid point P and its neighbors N-north, E-east, etc. All coefficients are positive and the coefficient matrix is diagonally dominant i.e.:

$$a_p \geq \Sigma a_d \qquad d = N, S, E, W, H \text{ and } L \qquad (2.4)$$

In the above formulae, a's represent the influences of convection and diffusion processes across the control volume faces.

EARTH assembles all a's and efficiently solves the system of the algebraic equations (2.3) for all grid points and for all dependent variables.

The solution procedure employed is based on the SIMPLE algorithm developed by Patankar and Spalding (Reference 12) in which the continuity equation is solved in terms of pressure corrections. The latest form of SIMPLE has been incorporated into PHOENICS. Another factor which influences the ability of PHOENICS to handle fine-grid problems, is the order of visitation which is selected when variables at cell-center are updated.

The order chosen involves what is called "repeated z-direction sweeps" through the integration domain (except for parabolic flows, for which only z-direction sweep is required). The whole set of cells is regarded as consisting of one-cell-thick "slabs", extending in the x and y directions, and piled one on top of the other in the z-direction.

A single sweep therefore starts with attention being paid to the bottom (low-z) slab of cells. The finite-domain equations are solved for all the cells in this slab, the values of ϕ's obtained at the next higher slab being regarded as known. Attention then passes to the second slab, the ϕ-values there being adjusted by reference to those in the slabs both above and below. Then the next higher slab is attended to; and so on, until the adjustment sweep has been completed. For the solution of pressure corrections, two options viz: a) slabwise solution, and b) the whole field solution, are provided.

Depending on the number of grid cells and problem nonlinearity up to a few hundred sweeps may be required before a converged solution is obtained.

Section 3
DESCRIPTION OF THE TEST CASE AND NUMERICAL MODEL

For demonstration of the computer code capability NASA MSFC specified the SSME geometry and operating conditions pertinent to the 100% power level. This section presents test case specifications, selected grid distribution, boundary conditions and assumptions of the mathematical model.

This section presents a discussion of geometrical aspects of the calculation domain and assumptions of the mathematical model.

3.1 Geometry of the SSME Thrust Chamber and Computational Grid

Figure 3.1 presents details of the thrust chamber geometry with dimensions. The wall coordinates of the expansion part of the thrust chamber have been provided in Reference 2 and in data specified by NASA.

A two-dimensional, axisymmetric, nonorthogonal body-fitted computational grid of NZ : NY = 41:20 control volumes has been selected for the computations. Figure 3.2 presents the computational grid. Figure 3.3 shows details of the grid distribution within the throat region.

A nonuniform grid distribution has been used with finer grid spacings in the regions of steep gradients viz: in the throat region, and near the chamber wall.

The grid has been generated by employing the power law, which in the radial direction, is as follows:

$$\frac{y(N-j)}{y(N)} = 1 - \left(\frac{j}{N}\right)^{\alpha} \qquad j = 1, 2, \ldots N-1 \qquad (3.1)$$

with $y(N) = 1$ and $\alpha = 1.5$.

Similar grid spacing variation has been obtained in the axial direction to concentrate the grid in the throat region.

Radii (R_T = 5.1527")

R_O/R_T	R_I/R_T	R_U/R_T	R_D/R_T	R_E/R_T
—	—	—	—	—
$\sqrt{3}$	1.73921	1.0	0.392	$\sqrt{77.5}$

Angles

θ_I	θ_D	θ_E
Degrees	Degrees	Degrees
25.4167	37	5.3738

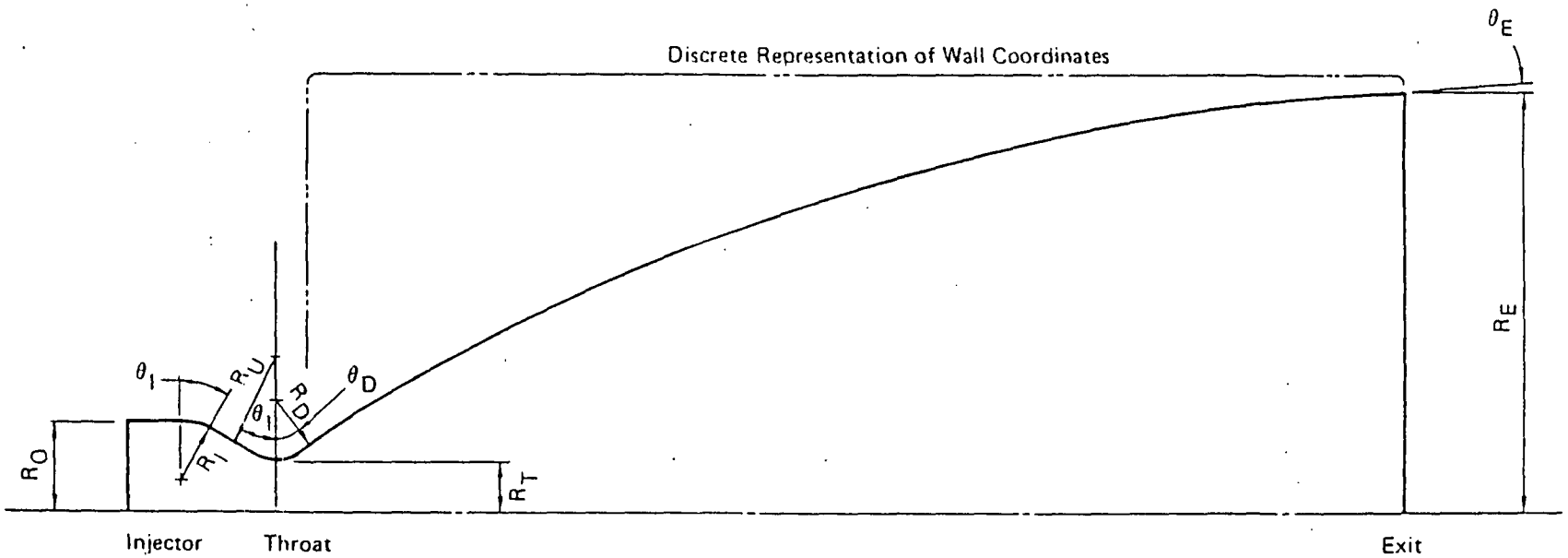

Figure 3.1. Details of the SSME Thrust Chamber Geometry

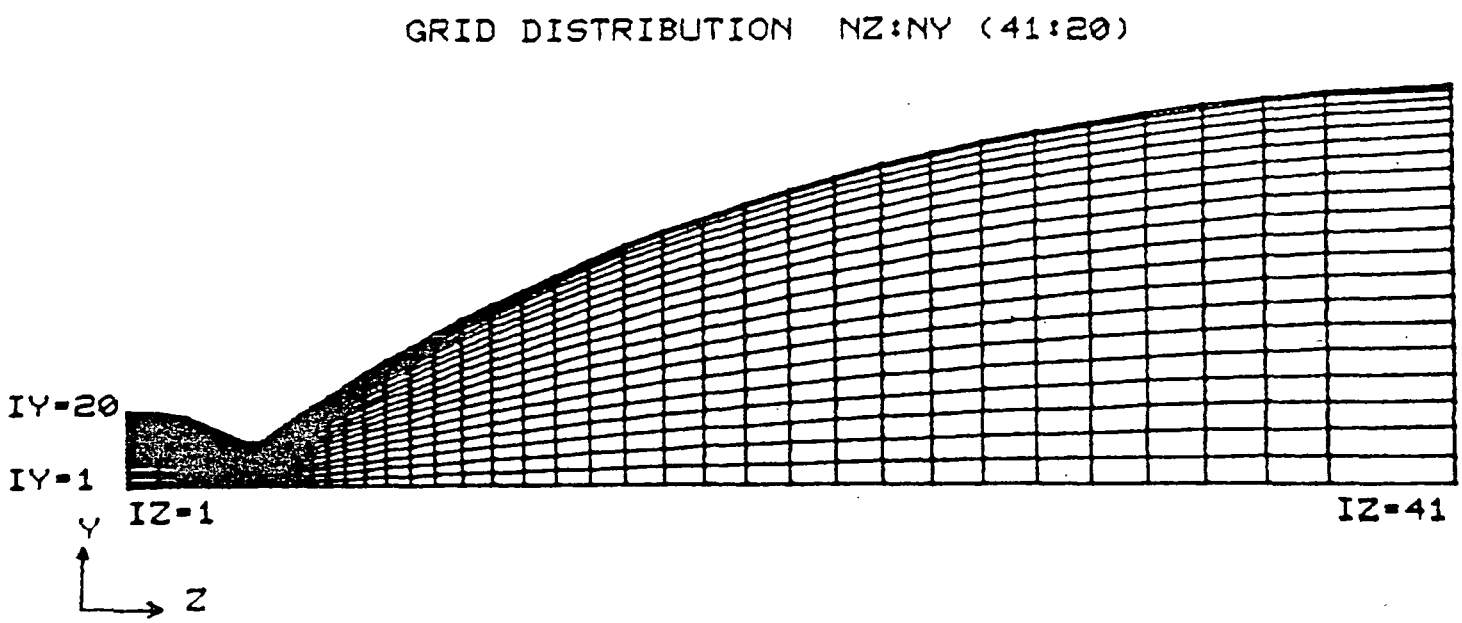

Figure 3.2 Grid Distribution of the SSME Thrust Chamber

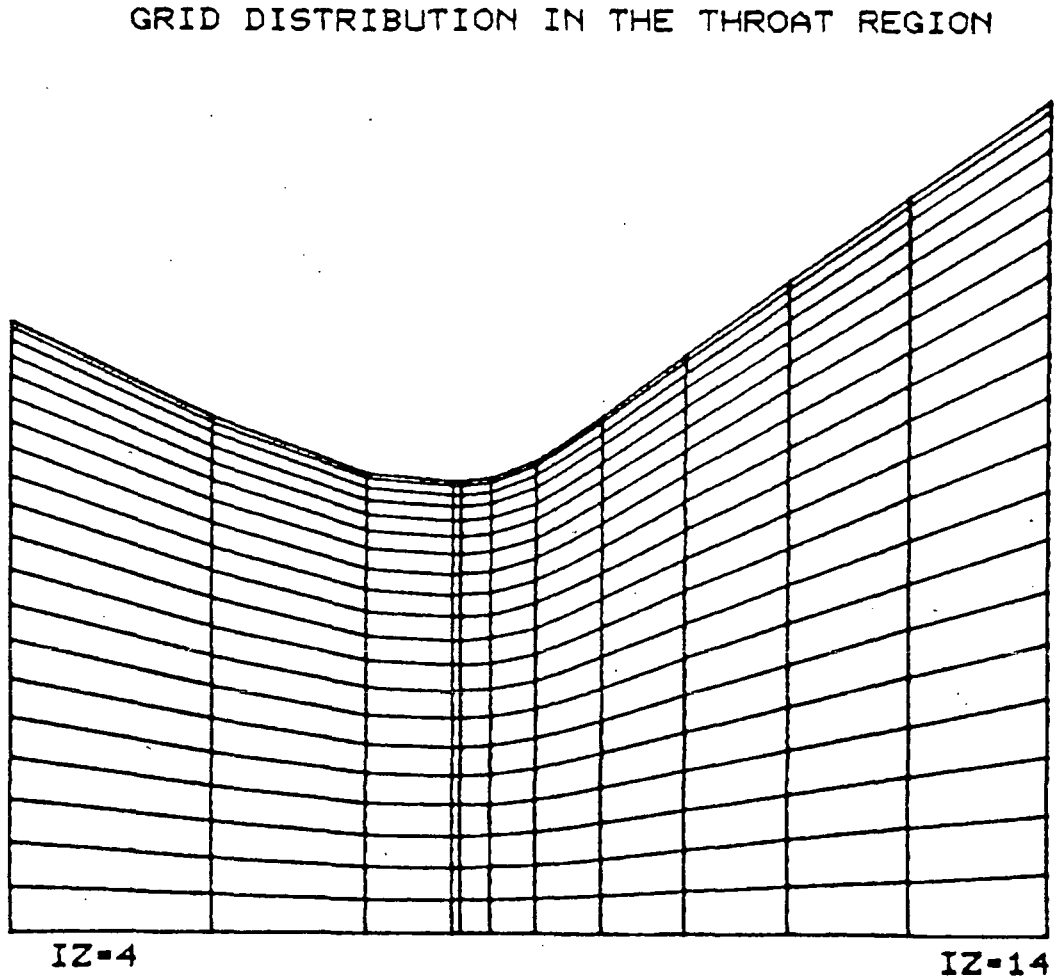

Figure 3.3 Enlarged View of the Grid Distribution Within the Throat Region

An extra column of grid cells IZ = 41 has been placed downstream of the nozzle exit to accomodate fixed pressure exit boundary conditions. This practice will permit for more accurate calculation of the radial pressure gradients at the exit of the nozzle. It should be pointed out however that for better resolution near the exit a few extra slabs would be required.

3.2 Physical Models and Assumptions

The fluid flow, heat and mass transfer processes are described in terms of first principles for the entire computational domain. These are briefly discussed below.

HYDRODYNAMICS

The Navier-Stokes equation considered here in its full elliptic steady two-dimensional form is:

$$\nabla \cdot \rho \bar{V} = 0 \tag{3.2}$$

$$\nabla \cdot (\rho \bar{V} \bar{V} - \mu \bar{\bar{\zeta}}) = - \nabla p \tag{3.3}$$

where $\bar{\bar{\zeta}} \equiv -\mu \left(\frac{\partial ui}{\partial xj} + \frac{\partial uj}{\partial xi}\right) + \frac{2}{3} \mu \frac{\partial ui}{\partial xj} \delta ij$ is the stress tensor.

The momentum equations are transformed to general nonorthogonal form, similar to that of equation 2.3, and integrated within each control volume.

The mixture density is calculated from the equation of state:

$$\rho = \frac{p \cdot \bar{M}}{R \quad T} \tag{3.4}$$

$$\text{where } \frac{1}{\bar{M}} = \Sigma\left(\frac{m}{M}\right)_j \qquad j = H_2, O_2, H_2O \tag{3.5}$$

and where R is the gas constant, $\bar{M}$ is the mixture molecular weight, m_j is the mass fraction and M_j is the molecular weight of specie j.

The effective viscosity in the momentum equations μ is calculated as a sum of laminar, μ_ℓ and turbulent, μ_t, viscosity.

$$\mu = \mu_\ell + \mu_t \tag{3.6}$$

TURBULENCE

The Cebeci - Smith turbulence model (Reference 37) used in the past thrust chamber calculations is a "two-zone" model which accounts for the pressure gradients in the viscous sublayer and employs a Prandtl model in the outer boundary layer zone. For the purpose of this calculation, however, a more general, high Reynolds number $k\sim\varepsilon$ turbulence model of Launder and Spalding (Reference 10) has been used. The assumptions of Cebeci - Smith models for the viscous sublayer have been used to derive new wall functions used in $k\sim\varepsilon$ model, which account for the pressure gradients. Details of the derivation and analysis are provided in Appendix B.

The turbulent viscosity is calculated as:

$$\mu_t = C_D \rho \frac{k^2}{\varepsilon} \tag{3.7}$$

where $C_D = 0.09$ is an empirical constant.

HEAT TRANSFER

For heat transfer calculations, the total energy ($\tilde{h}$) is used as the dependent variable in energy conservation equation.

For a premixed fuel and oxidizer composition, total energy is defined as the sum of enthalpy and kinetic energy:

$$\tilde{h} = \sum_j h_j + \frac{w^2}{2} \tag{3.8}$$

$$\text{where } h_j = m_j \int_{298}^{T} C_{pj} dT + h^o_{f298j} \tag{3.9}$$

In the above relations summation is taken over all species, w is the local velocity, C_{pj} is the specific heat and h^o_{f298j} is the enthalpy of formation.

The specific heat C_{pj} is calculated as a function of temperature as follows:

$$\frac{C_p}{R} = a_1 + a_2 T + a_3 T^2 + a_4 T^3 + a_5 T^4 \tag{3.10}$$

where $a_1 \ldots a_5$ are constant coefficients given for each mixture component for two temperature ranges 300 - 1000K and 1000 - 5000K.

For an adiabatic flow, $\tilde{h}$ is constant throughout the calculation domain and therefore the energy equation does not have to be solved for. Temperatures can be calculated from algebraic relations (Equations 3.8 and 3.9). For a non-adiabatic flow, the wall heat transfer rate is determined from the Chilton-Colburn form of the Reynolds analogy:

$$\dot{q}''_w = St \cdot \rho|w| \cdot (\tilde{h}_p - \tilde{h}_w) \tag{3.11}$$

where $\tilde{h}_p$ is the total enthalpy at the grid node in question;

$\tilde{h}_w$ is the enthalpy corresponding to the prescribed wall temperature;

ρ is the mixture density;

$St = C_f \, Pr^{-2/3}$ is the Stanton number related to the friction coefficient C_f;

$$C_f = \frac{\tau_w}{\rho W^2} \text{ ; and} \tag{3.12}$$

τ_w is the wall shear stress calculated from the wall functions (see Reference 10; see also Appendix B).

The energy equation is solved in the following form:

$$\text{div} \, (\rho \vec{V} \tilde{h} - \Gamma \text{grad} \, \tilde{h}) = S_{\tilde{h}} \tag{3.13}$$

where $\Gamma = \mu_{eff}/Pr$ is the transport coefficients and $S_{\tilde{h}}$ is the source term which, in general, should include the radiation energy transfer term and dissipation function ϕ.

$$\phi = - \nabla \cdot (\bar{\bar{\tau}} \cdot \vec{V}) \tag{3.14}$$

which represents the rate of viscous forces energy transfer to thermal energy i.e. mechanical to interal energy transfer (for details, see Bird, Steward and Lightfoot, "Transport Phenomena", page 313).

In this study, however, both radiation and viscous dissipation terms are neglected.

Rigorous combustion calculations would require a full chemical kinetics model with transport equations for all species (H_1, H_2, OH, O_1, O_2, H_2O, HO_2, ...).

At high temperatures and pressures, the reaction rates are so fast in both directions that the chemical equilibrium is reached. In this case local composition can be determined from the prevailing pressure and temperature based on the Gibbs function minimization principle.

In the present demonstration project, however, the simple approach of a one step reaction:

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O \tag{3.15}$$

has been applied with global reaction rate equal to slowest limiting chain propagation reaction viz:

$$M + H + O_2 \rightleftarrows H_2O + M \tag{R1}$$

This reaction, is of primary importance for fuel-rich flames in the main flame zone (Reference 14). Downstream of the flame front, within the throat and nozzle regions, recombination reactions become dominant. The reaction rate expression employed in present calculations is:

$$R_f = 2 \cdot (H_2)\ (O_2) * 1.2\ 10^9 \exp(-800/T) \tag{3.16}$$

The terms in brackets are molar fractions with units in kg. moles/m^3 giving rates in moles/sec.

The fuel mass fraction m_{H_2} is calculated by solving the transport equation:

$$\text{div}\ (\bar{V} m_{H_2} - \Gamma \text{grad}\ m_{H_2}) = R_f \cdot \tag{3.17}$$

The calculations of the remaining stable species concentrations m_{O_2} and m_{H_2O} are obtained from stoichiometric relations.

$$m_{O_2} = 8 \cdot (m_{H_2} - m^B_{H_2})\ ; \quad \text{and} \tag{3.18}$$

$$m_{H_2O} = 1 - m_{H2} - m_{O2} \tag{3.19}$$

where m^B_{H2} is the m_{H2} concentration at "fully burned stage" (in current case when $m_{ox} = 0.$), defined as:

$$m^B_{H2} = m^0_{H2} - \frac{1}{8} m^0_{O2} \tag{3.20}$$

where superscript "0" indicates condition at the inlet (prior to combustion).

Alternative, more adequate, combustion models for thrust chamber calculations are discussed in Section 5 as recommended for future study.

3.3 Boundary Conditions

For the two-dimensional computational domain, the boundary conditions should be specified at: inlet, exit, nozzle wall and symmetry plane, for all dependent variables, including:

ϕ = w - axial velocity
v - radial velocity
k - kinetic energy of turbulence
ε - dissipation rate
$\tilde{h}$ - total enthalpy
m_{H2} - fuel mass fraction

In the present calculations the boundary conditions are specified as follows.

3.3-1 Inlet

At the inlet to the combustion chamber uniform profiles for all dependent variables have been assumed. These are specified as follows:

- total pressure: $p_T = 2935.7$ psi $= 202.4 \cdot 10^5$ N/m^2
- radial velocity: $v = 0$
- axial velocity: w is calculated by the code based on the specified fixed inlet pressure
- enthalpy: $\tilde{h} = \Sigma (C_p T_T + h_f^o)$
- species composition: m_{H_2}, m_{O_2}, m_{H_2O} are calculated from given inlet mixture ratio f = 6.054851 and given inlet enthalpies $h_{H_2} = 1837.660 \frac{cal}{mol} = - 3.84695 \cdot 10^6 \frac{J}{kg}$
  $h_{O_2} = - 2884.385 \frac{cal}{mol} = - 3.77386 \cdot 10^5 \frac{J}{kg}$

Details of the calculation for the inlet properties (m_{H_2}, m_{O_2}, m_{H_2O} and $T)_{inlet}$ are provided in Appendix A.

- k and ε — Initial values for k and ε are estimated on the basis of inlet turbulence intensity of 10% and, length scale of 0.01 times the inlet chamber diameter. For the high-Reynolds number flow in question, results are not expected to be sensitive to the inlet k and ε values.

3.3-2 Symmetry Plane (Axis)

At the symmetry plane the radial velocity v is set to zero while for all other dependent variables a zero normal gradient has been imposed.

3.3-3 Exit

For hyperbolic or parabolic equations (solved by TDK and BLIMP code respectively) no exit boundary conditions are required. For fully elliptic calculations, however, a downstream boundary condition is necessary. A fixed exit pressure, uniform across the flow direction, has been imposed at the last slab (just downstream of exit plane). Although an approximate static pressure gradient for the SSME exit plane has been provided, it was decided not to use it. For the present project it would have increased the accuracy of the results in the exit plane domain. However, in a prediction mode for other thrust chambers this information is normally not available. Furthermore, the assumption of a constant pressure as a downstream boundary condition would yield results indicating, how far upstream this assumption would influence the calculated data. For the remaining dependent variables "locally parabolic" assumption at the exit plane has been employed which permits to calculate ϕ-values at the last slab from upstream ϕ-values.

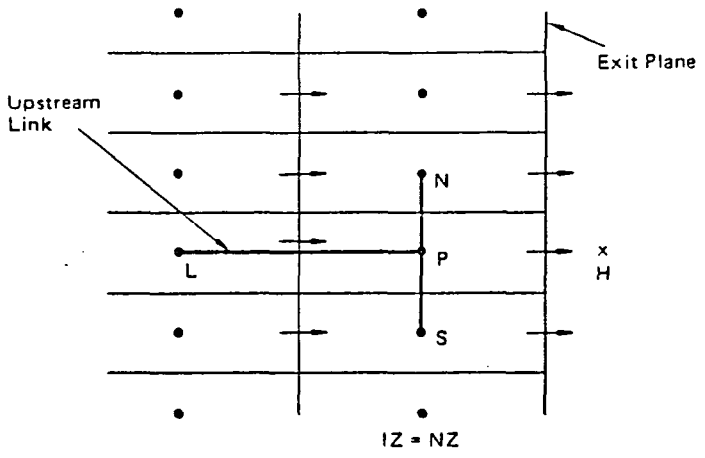

Figure 3.4 Exit Boundary Condition Specification

3.3-4 Solid Wall

At the solid wall "no slip" boundary conditions are imposed.

Special attention is required for calculating "near wall" shear stresses and heat fluxes where transport properties as well as dependent variables often vary steeply in the neighborhood of a wall. For this purpose semi-analytical solutions, called "Wall Functions" are used.

Appendix B presents the basic principles of the wall functions for compressible flows with significant pressure gradients.

3.4 Flow Field Initialization

The starting conditions for steady state calculations are arbitrary. A "good" guess, however, can significantly improve the convergence rate. For the purpose of this study the initial flow fields have been generated from the isentropic flow relation for the nozzle (Reference 15).

$$\left(\frac{A}{A^*}\right)^2 = \frac{1}{M^2}\left(\frac{2}{\gamma+1} + \frac{\gamma-1}{\gamma+1} M^2\right)^{\frac{\gamma-1}{\gamma+1}} \qquad (3.21)$$

For a given γ = 1.3 and local area to throat area ratio one can calculate local Mach number M_o and then the local velocity, total temperature, total pressure and density. At the throat where $A/A^* = A/A_{throat} = 1$ the flow is assumed to be choked. A uniform total enthalpy equal to the inlet enthalpy and a uniform m_{H2} mass fraction equal to the "fully burned" equilibrium value in the combustion chamber have been assumed throughout the domain.

3.5 Under-Relaxation

In the steady state calculations the sweep-to-sweep solution variation is controlled by the under-relaxation of dependent variables. The solution control is exercised by relaxing the pressure, velocity and density. Pressure and density are relaxed by the direct relation i.e.

$$\rho^n = \rho^* \alpha_\rho + \rho^{n-1} (1-\alpha_\rho) \tag{3.22}$$

$$p^n = p^{n-1} + p' \alpha_p \tag{3.23}$$

where: α - relaxation parameter;
ρ^* - currently calculated density;
p^{n-1}, ρ^{n-1} - previous iteration values;
p' - pressure correction.

The axial and radial velocities are relaxed by adding an inertia term to the relevant finite difference transport equation:

$$\phi_p = \frac{\Sigma a_i \phi_i^* + \frac{\rho VOL}{\Delta t_F} \phi^*}{\Sigma a_i + \frac{\rho VOL}{\Delta t_F}} \qquad i = E, W, N, S, H \text{ and } L, \tag{3.24}$$

where ϕ stands for any dependent variable; a_i is the link coefficient (representing convective and diffusive fluxes through the control volume faces); VOL is the volume of the grid cell; and Δt_F is the "false time" step used to control under-relaxation. Note that a smaller Δt_F value implies heavier under-relaxation.

In the present study the relaxation factors were modified during the calculations. For example the false time step Δt_F for velocity components were set to:

$\Delta t_F = .01 \cdot r_{Throat}$ for iteration 1 to 100;
$\Delta t_F = .1 \cdot r_{Throat}$ for iteration 100 - 300;
$\Delta t_F = 1000\ r_{Throat}$ for iteration 300 and up.

Pressure relaxation has been gradually varied from $\alpha_p = 0.3$ to $\alpha_p = 0.6$.

Section 4

INPUT DATA PREPARATION

Input data preparation for the PHOENICS run requires user's input via the SATELLITE program and the GROUND subroutine. The input data are supplied in the form of FORTRAN statements. Both SATELLITE and GROUND are user oriented self-explanatory subroutines with divisions into specific-purpose sections and comment statements. In this chapter the description of the input data for the SSME NOZZLE test case is discussed. For general information about data preparation, the PHOENICS Instruction Manual (Reference 5) is recommended. Listings of the adapted SATELLITE and GROUND are provided in Appendix E. It is suggested that the reader who is not directly interested in the code execution procedure or in the studying of the coding implemented in SATELLITE and GROUND can skip the following two sections and continue onward from Section 5.

4.1 Information Supplied Via Satellite

The SATELLITE Program is divided into 43 Chapters of which Chapters 3 to 33 were used in the present demonstration case. Each chapter has the COMMENT heading and commented default variable specifications in <> brackets. A user may override the relevant variables.

Grid and geometry are specified in Chapters 3 to 7 (see Figures 3.1 and 3.2). For the present two-dimensional case, in y-z (radial-axial coordinates) frame, XFRAC - nondimensional distance in circumferential coordinate is set to 1 in Chapter 3. In Chapter 4 loop DO 400 is used to specify the nondimensional grid distribution in radial direction. NY=20 is a number of grids, POWER is the nonuniformity factor (POWER=1 provides uniform grid) and THROAT = 0.13099 is the throat region. The geometric shape of the nozzle is also specified in Chapter 5. In this case a "NOZZLE.DTA" file is read-in, containing $(Z-Z_{throat})/r_T$ and y_{wall}/r_T data. Current geometry data reflect the wall contour and is exactly the same as used in the BLIMP program. NTAB = 393 is the total number of wall coordinates and NTABT = 31 is the throat coordinate location in the table. Array OZZLE (393, 2) contains these wall coordinates. In loops DO 500 and DO 501 nondimensional ZFRAC-axial grid line coordinates are specified. Note that the zero location in the z-axis is at the inlet to the nozzle, not at the throat.

At the end of Chapter 5 an extra grid cell slab is added after the real nozzle exit and total number of grids is incremented by 1.

In Chapter 6 the BFC = .TRUE. statement is set for nonorthogonal body fitted coordinate system. In DO 601 loop the arrays YN (NX, NZ, 1) and YS (NX, NZ, 1) are specified to north and south (wall and axis) y-coordinates of the nozzle. YN, used for nozzle wall coordinates, is interpolated from OZZLE array for each IZ, and YS is set to zero at each IZ since the south boundary is the axis of the nozzle. In double loop DO 605, DO 604 circumferential direction boundaries are specified as one hundred of a radian. In DO 605, DO 606 high ZH and low ZL arrays are arranged such that ZL(IZ)=0 at the inlet and ZH(IZ)=ZFRAC (NZ)* THROAT is equal to the total nozzle length (including the extra grid cell).

DEPENDENT VARIABLES - to be solved and stored are specified in Chapter 8. The indices of the SOLVAR and STOVAR indicate selected variables i.e. P1 - pressure, PP - pressure correction, V1 - radial velocity resolute, W1 - axial velocity resolute, C1 - first concentration used for m_{H_2} mass fraction, KE and EP for $k\sim\varepsilon$ turbulence parameters, H1 for enthalpy, H2 is used for temperature storage, U2, V2, W2 arrays will be used for storing the cartesian velocity components and storage 16 and 21 for nonorthogonal (contra-variant) velocity components and storage 23 will be used for saving continuity errors. Chapter 9 provides user specified titles to the variables.

PROPERTIES - In Chapter 10, longest section of the satellite, physical properties of the test case are specified. SIGMA (24) and SIGMA (14) arrays contain the laminar and effective Prandtl numbers, EMULAM = 0.000102 is the laminar viscosity and IRHO1 = -1 indicates that the density ρ will be specified in GROUND (also in Chapter 10).

In the remaining part of Chapter 10 of SATELLITE, properties at the inlet to the nozzle are specified. The variable names are arbitrary and "local" in SATELLITE. FMIX = 6.054851 is the mixture fraction, SMO(1), SMO(2) and SMO(3) are used for initiating mass fractions of H_2O, H_2 and O_2, respectively. ENTHMIX is set to inlet mixture enthalpy as described in Appendix A.

DO 1777 loop has been initially used to estimate inlet concentrations at TEMP = 300^{o}K. The pertaining calculation procedure is also described in

Appendix A. Array SC contains molar concentrations of H_2O, H_2 and O_2 at inlet for T = 300^oK; SC [kmol/kg]. FMUB = 2.SC(2) specifies the mass fraction of the "unburned" hydrogen and the next three statements override SC to represent a relative mixture composition in the fully burned stage. Note SC(3) = 0, i.e. $m_{O2}^B = 0$ as $f < f_{stoic}$.

CALL TEMPER passes the execution to a subroutine which calculates temperature TEMP for particular enthalpy HHH and gas composition SC. The variable TTEMPR is the initial "guess" of TEMP with RGAS = R = 8305 representing the gas constant and CPDR = C_p/R the specific heat. All data are entered in SI units. CALL ENTHAL statement is used to calculate the mixture enthalpy ENTH = $\tilde{h}/R$ and specific heat CPDR = C_p/R for given temperature TEMP and composition SC of three components. Both ENTHAL and TEMPER listings follow the listing of SATELLITE.

WTMOL is the mean molecular weight of the "burned" composition. H2SAT = $\tilde{h}$ = RGAS.ENTH is used to transfer the total enthalpy $\tilde{h}$ to the GROUND where it could be used for "adiabatic" test case. If H1 is solved for the H2SAT is not used.

CALL MSOLV statement is used twice in the remaining part of this chapter. At first to calculate the inlet isentopic condition with given GA = γ = 1.3 and AAT inlet to throat area ratio and secondly to calculate exit pressure. AM = 0 and AM = 2 are the "guess" Mach numbers at the inlet and throat cross-sections which will be iteratively calculated in the MSOLVE subroutine.

INITIAL FLOW FIELDS are specified in Chapter 13 via variable FIINIT. Note that only the H1 enthalpy is initialized as constant equal to H1SAT = H2SAT.TTOT (set just after the statement 6744). Remaining flow field variables P1, W1, C1 and H2 (for temperature) are specified in a FLDDAT subroutine called at the end of SATELLITE, the listing of which is included in Appendix E. FIINIT = 10101 indicates that particular variable will be specified in FLDDAT. Note that V1 is not specified since the default value (1.E-10) is used.

BOUNDARY CONDITIONS are set up in Chapters 14 and 15 by specifying the "REGIONS" at the inlet (Region 1) exit (Region 2) and nozzle wall (Region 3). No region specification is required for the axis because the symmetry plane is a default region specification.

CALL PLACE (IREGN, TYPE, IXF, IXL, IYF, IYL, IZF, IZL) is used to specify the grid control cells in the region in question.

CALL COVAL (IREGN, VARIABLE, COEFF, VALUE) is used to specify the boundary conditions for dependent variables. The boundary flux of the ϕ-variable is calculated as:

$$\dot{m}\phi = [S_m + C_\phi] (V_\phi - \phi) \tag{4.1}$$

where ϕ is the inner, adjacent grid node value to be calculated implicitly in PHOENICS, VALUE or v_ϕ is the ϕ-value at the boundary, C_ϕ = COEFF is the diffusional flux coefficient of ϕ and S_m is the mass source at the boundary, S_m is calculated as:

$$S_m = C_m (V_m - p) \tag{4.2}$$

where V_m is either desired mass flow rate or external pressure depending on the type of the boundary condition, p is the pressure in the control cell adjacent to the boundary (incorporated implicitly by PHOENICS) and C_m is the mass flux coefficient. $C_m = 10^{-10}$ for fixed flow rate or a desired "resistance" related value for the fixed pressure boundary condition. Detailed derivation and discussion of the boundary condition specification is provided in Appendix C. Note that ONLYMS $\equiv$ 0 indicates no diffusive link at the boundary. Note also that region 3 CALL COVAL statements are COMMENTed as the wall functions for all variables are calculated (in GROUND) by using a pressure gradient dependent formula.

SOLUTION CONTROL AND RELAXATION parameters are specified in Chapters 26 to 34. For compressible flows, LOGIC (87) = .TRUE. is set in Chapter 26. FSWEEP = 401 and LSWEEP = 450 indicate a restart run from results of 400 sweeps calculated prior to the current run. For the new run set FSWEEP = 1.

In Chapter 29 the pressure relaxation factor FLXP and velocity under-relaxation parameter DTFALS are specified. This rather strong relaxation is reduced, in GROUND, after the first 50 sweeps.

In Chapter 32 the logical arrays PRINT can be activated for whole field printout of desired variables. IZMON, IYMON are the grid coordinates of the

control volume values of which the (W1, P1, T ...) will be printed during the course of iterations (at each sweep). Variable NYPRIN = 2 will cause skipping of each second IY line from the output (NYPRIN = 1 can be used for full printout).

RESTART run is specified in Chapter 42 where SAVEM = .TRUE. will activate result dump on the disk (file name TM1) which can be used for restart of graphical postprocessing.

Finally, in the user independent section, calling subroutine FLDDAT initial flow fields are prepared for all variables specified in Chapter 13.

Additional subroutines attached to satellite are:

SUBROUTINE TEMPER with input HSTAT - static enthalpy, TO - initial guess for temperature, SC (NSC) - species molar concentrations in [kmol/kg] and RGAS = 8305 gas constant. The result of the calculations is T - temperature and CPDR = C_p/R. There is no user input required to this subroutine.

TEMPER is called by SATELLITE and calls subroutine ENTHAL.

SUBROUTINE ENTHAL - with input of: TEMP, and SC (NSC) returns mixture specific heat and enthalpy calculated as follows:

$$\frac{C_p}{R} = Z_1 + Z_2T + Z_3T^2 + Z_4T^3 + Z_5T^4 \tag{4.3}$$

$$\frac{h}{RT} = Z_1 + \frac{Z_2T}{2} + \frac{Z_3T^2}{3} + \frac{Z_4T^3}{4} + \frac{Z_5T^4}{5} + \frac{Z_6}{T} \tag{4.4}$$

$$\text{where } h \equiv h^o_{f,298} + \int_{298}^{T} C_p \, dT \tag{4.5}$$

Coefficients Z_1 to Z_6 should be supplied via DATA statements in ENTHAL using the array ZA(7, 2, NSC). Current data are valid for T = 300 - 5000^{o}K for H_2O, H_2 and O_2 and are taken from JANNAF tables.

SUBROUTINE MSOLV is called by SATELLITE and by FLDDAT to calculate isentropic flow properties. The input is GA = γ = 1.3, KS = 1 for supersonic and KS = 0 for subsonic flow, AAT - local to throat area ratio and AM - initial guess for

Mach number (e.g. Ma = 0 for subsonic and Ma = 2 for supersonic). The result of iterative calculations is the correct Mach number, and

$$VRT \equiv Ma \sqrt{\frac{\gamma R}{T_t/T}} \tag{4.6}$$

$$QRT = Ma \sqrt{\frac{\gamma}{R}} \left(\frac{T}{T_t}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \tag{4.7}$$

$$TTT = 1 + \frac{\gamma-1}{2} Ma^2 \tag{4.8}$$

$$PTP = \left(\frac{T_t}{T}\right) \tag{4.9}$$

which are used in SATELLITE and FLDDAT to calculate local isentropic properties.

SUBROUTINE FLDDAT - is called from SATELLITE and shares with SATELLITE common block CMNBF1 (listing included after FLDDAT List). User dependent part starts in Chapter 2 where in two DO loops over IZ and MPH1 (variables) initial fields for P1, W1, H2 = TEMP and C1 - m_{H_2} are set up. Note that within the loops CALL MSOLV brings local cross-section isentropic parameters. Array PHI (IY, IZ) is used for initialization.

4.2 User Supplied Coding Via GROUND

The GROUND subroutine is accessed by EARTH at several stages of the solution. It has 16 chapters of which only the first 10 are used in the present test case. The COMMENT statements indicate when a particular chapter is being called by EARTH. User dependent section starts under the comment CXXX ... X USER SECTION 1 STARTS (see on page 1 of GROUND, Appendix E), where one must specify the array dimensions for CVAR, VVAR, CM, VM and ZERO to be (NY, NX) i.e. for the current test case (20, 1). Any number of local variables and arrays, with proper dimensions, can be introduced in GROUND. It is advised to start FORTRAN names for arrays and real values with the letter G (GP - for pressure, GW - for w-velocity, GTWALL - for wall temperature, etc.) This will ensure no conflict between local variables and variables provided by GROUND station and EARTH COMMON blocks.

Further downstream, a user can insert adequate DATA statement e.g. DATA RGAS/ 8305.6/DATA ARFC, CRCF, ARCR CRCR/3.7656E7, 800, .../ where the second set of

data defines Arrhenius reaction rates for forward (F) and reverse (R) reactions. Subsequently each chapter is briefly discussed.

CHAPTER 0 - is called at the start of the run. Specific constants are set or calculated e.g. GPI = 4. arctg (1.) = π . NXP1 = NX + 1, etc. Also file 23 holding grid vertices (file name BFCXYZ) is opened. Finally subroutine WALDP is called to initialize some constants in it.

CHAPTER 2 - in our test case will be called only once at the beginning of the run. Here the wall temperatures are calculated by calling SUBROUTINE TWALBC (discussed below) the input is NZ, GZNODE - nondimensional axial coordinates of the grid cell slabs, and ZTHRO - throat distance from the inlet. In DO 3120 loop GZCELL (distance from the inlet) and GYWALL (local radius of the nozzle) are recovered from stored data of grid vertices on file BFCXYZ with Logical Unit 23. (These data were written by SATELLITE.) Finally wall inclination angles are calculated in DO 3140 loop.

CHAPTER 3 - is used to gradually adjust the under-relaxation factors from sweep 50 to sweep 150. This coding is test case depended and may not be optimal for the test case in question. It is assumed that more than 150 sweeps are necessary after which the relaxation is frozen. In the particular test case of the SSME nozzle approximately 400 sweeps are anticipated. Variables RLXP, RLXPZ, RLXPXY as well as Array DTFALS (NVAR) are EARTH variables available in GROUND.

CHAPTER 5 - is used to specify source terms. As explained in Appendix C several physical processes can be simulated by providing appropriate "values and coefficients" of the linearized source term formula:

$$\text{SOURCE} = [C_m\ (V_m - P) + C_\phi]\ (V_\phi - \phi) \tag{4.10}$$

In our test case $C_m = V_m = 0$ and attention is focussed only on C_ϕ and V_ϕ (CVAR, VVAR) coefficients with SOURCE = $C_\phi\ (V_\phi - \phi)$. In the first part of Chapter 5, the reaction rate for m_{H_2} is calculated as:

$$R = -A.e^{-C/T}\ .\ \rho^2\ .\ m_{H_2}\ m_{O_2} \tag{4.11}$$

The linearization of above gives:

$$R = R^* + \frac{\partial R^*}{\partial m_{fu}} (m_{fu} - m_{fu}^*) = R^* + \frac{R^* - 0}{m_{fu}^* - m_{fu,eq}} (m_{fu} - m_{fu}^*) =$$

$$= \frac{-R^*}{m_{fu}^* - m_{fu,eq}} (m_{fu,eq} - m_{fu})$$

$$R = \frac{A e^{-C/T} \rho^2 m_{H_2} m_{O_2}}{m_{H_2}^* - m_{H_2,eq}} (m_{H_2,eq} - m_{H2}) \qquad (4.12)$$

$$C_\phi = \text{CVAR} \qquad V_\phi = \text{VVAR}$$

where $m_{H_2}^*$ - is the previous sweep fuel mass fraction;

m_{O_2} - oxygen mass fraction [$m_{O_2} = f_{stoic} \cdot (m_{fu}^* - m_{fu,eq})$] ;

A,C - Arrhenius rate constants set by the DATA statements as discussed above;

ρ - mixture density (array RHO (IY,1))

Coding for the calculation of CVAR and VVAR is executed in DO 508 loop.

Note that CALL GET statements are used to "get" portions of the EARTH's F-array and "copy" it to appropriate GROUND station array e.g.:

```
CALL GET (C2, CFU, NY, NX)
```

accesses C1 $\equiv m_{fu}$ section of F-array and sets it into user's array CFU dimensioned (NY, NX) at the beginning of GROUND.

After the CVAR and VVAR are calculated they have to be placed into the appropriate position of the F-array. For this purpose the CALL ADD statement is used e.g. CALL ADD (C1, 1, NX, 1, NY, VOLUME, CM, VM, CVAR, VVAR, NY, NX) where C1 indicates the variable name, the following four integers define the grid cells range at the IZ-slab, VOLUME indicates that the source term is calculated per unit volume, CM = VM = 0 i.e. no mass addition is envisaged, CVAR and VVAR are the calculated coefficient and value of the source and NY, NX are dimensions of the CM, VM, CVAR, VVAR arrays.

In the remaining part of Chapter 5 wall functions are used to calculate the wall shear stress, wall heat flux and near wall k∿ε values. Between label 515 and 517 local (IZ) near wall pressures, velocity and density are extracted from appropriate arrays GP, GRH. GPRL = SIGMA (24) is the laminar Prandtl number, set in SATELLITE. Four sections starting with labels 517, 520, 530 and 540 call subroutine WALDP where wall functions are calculated. The input parameters are: IZED - current slab number, ISWP - sweep number, NZ - total number of slabs, 1 - variable index 1-W, 2 - $\tilde{h}$, 3 - k and 4 - ε, GDYNY distance to the wall from the "near wall" grid node, EMULAM - laminar viscosity set in SATELLITE, GWFD1, GWFW1-w, two Prandtl numbers Pr_L, Pr_t, GWFP1H - current slab and higher slab pressures, and finally, GDZ - ΔZ. The result calculated in WALDP is "VALUE" and "COEFFICIENT" set into CVAR (NY,1) and VVAR (NY,1) and representing the near wall source term coefficients. Note that VVAR (W1) = 0 specifies a no slip condition at the wall and VVAR (H1) = $\tilde{h}$ + Cp (T_w - T) is the wall enthalpy. The coefficients are wall shear stress and wall heat flux, respectively. Wall functions for k and ε are used to calculated "fixed near wall" k and ε.

CHAPTER 7 - in the current test case calculations of dependent variables including GATT, GFLXT - throat area and throat mass flow rate, GAEXT, GFLXE - exit area and exit mass flow rate are conducted for the last sweep only. In DO 772, DO 773, and DO 774 loops axial components of the wall pressure forces are computed. Next thrust and specific impulse are calculated and printed. In the last part of Chapter 7 significant selected variables are printed.

CHAPTER 10 - is used to calculate density and temperature. In DO 1010 loop species molar concentrations are determined from the known m_{H_2} - mass fraction, and molecular weight WTMOL. GEKIN is the kinetic energy equal to 0.5 ($w^2 + v^2$) and GHSTAT is the static enthalpy. The CALL TEMPER statement provides a new local temperature related to the current concentration and static enthalpy. In the last three statements before 1010 label the density (from the equation of state), the temperature and specific heat are calculated. The listing and discussion of TEMPER subroutine is provided with the SATELLITE description.

CALL SET is used to set local arrays GRM and GTEMP into the F-array storage. In the second section of Chapter 10 selected axial and near wall pressures and temperatures are saved for later printout purposes. In the last sweep within the DO 1050 loop the Mach number is calculated for the entire flow field and set into the F-array via CALL SET (C2, ...). Remember that the C2 - "second concentration" memory is being used to save and then print the complete Mach number field.

SUBROUTINE TWALBC - is prepared to specify the temperature along the nozzle wall. User places ZTWQ and TQW arrays via the DATA statements. Within this subroutine a linear interpolation is employed to calculate the temperatures at the grid node locations from temperature data specified at locations along the wall. The User is advised to verify the resultant T_{WALL} array which is being printed from the DO 5555 loop at the end of this subroutine.

SUBROUTINE WALDP - calculates VALUE and COEFFICIENT for the near wall source terms W1, $\tilde{h}$, k and ε. The first section, up to statement no. 100 is accessed only once for initialization of prespecified constants. Between label 100 and 120 local velocity - WP, density RHOP and pressure gradient DPDZP are calculated. PPC is a constant in the $p^+ \sim u^+$ formula.

RE is the Reynolds number calculated based on the control volume characteristic distance (cell size) near wall velocity and laminar viscosity.

Further coding is divided into three parts:

- up to label 212 wall functions for w and $\tilde{h}$ are implemented;
- between label 300 and 400 wall functions for k - turbulent kinetic energy is coded; and
- after label 400 - the ε wall functions are specified.

The programmed analytical formulations for the wall functions are provided in Appendix B.

Section 5

PRESENTATION AND DISCUSSION OF COMPUTATIONAL RESULTS

The main objective of the present study is to demonstrate the capability of simulating reactive, compressible elliptic flows within the combustors and nozzles of a thrust chamber. This section presents the computed Navier-Stokes solution of the specified test case, already described in Section 3.

5.1 Presentation of Results

Figure 5.1 presents velocity vectors within the combustor and nozzle. Details of the velocity vectors within the throat region (IZ = 4 to IZ = 14) are shown in Figure 5.2 and velocity profiles at selected axial cross-sections are shown in Figure 5.3. Figure 5.4 shows Mach number contours with uniform contour levels distributed between $Ma_1 = 0.2$ to $Ma_{20} = 4.0$. The location of Ma = 1 contour is presented in Figure 5.5. Figure 5.6 presents contour lines of the absolute value of static pressure p [N/m^2]. The scale of pressure contour levels is non-uniform and the range varies from $p_1 = 10^4$ to $p_{20} = 2.10^7$ N/m^2. In Figure 5.7 contours of absolute temperature T [^oK] are shown. The range of temperature contour levels is uniform and varies from T = 1500 ^oK (Contour 1) to T = 4000^oK (Contour 20).

Figure 5.8 provides axial variations of absolute temperature at three radial locations:

- T_W - wall temperature (input data);
- T_{NY} - last grid cell near wall temperature ($y/y_w \cong 0.994$); and
- T_{AX} - temperature along the axis of the nozzle.

Finally Figure 5.9 presents similar variations of static pressure in absolute values along the solid wall and along the axis.

Detailed numerical information of the flow field is provided in Tables 1 to 8. In Table 1 an output summary in SI units is presented where the headings have

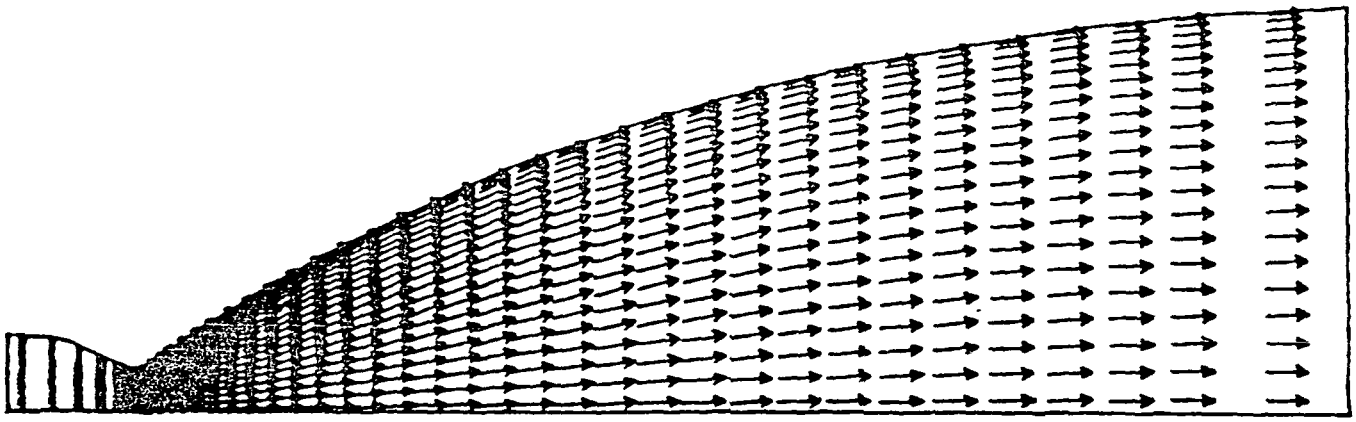

Figure 5.1 Calculated Velocity Vectors Within the Combustor and Nozzle

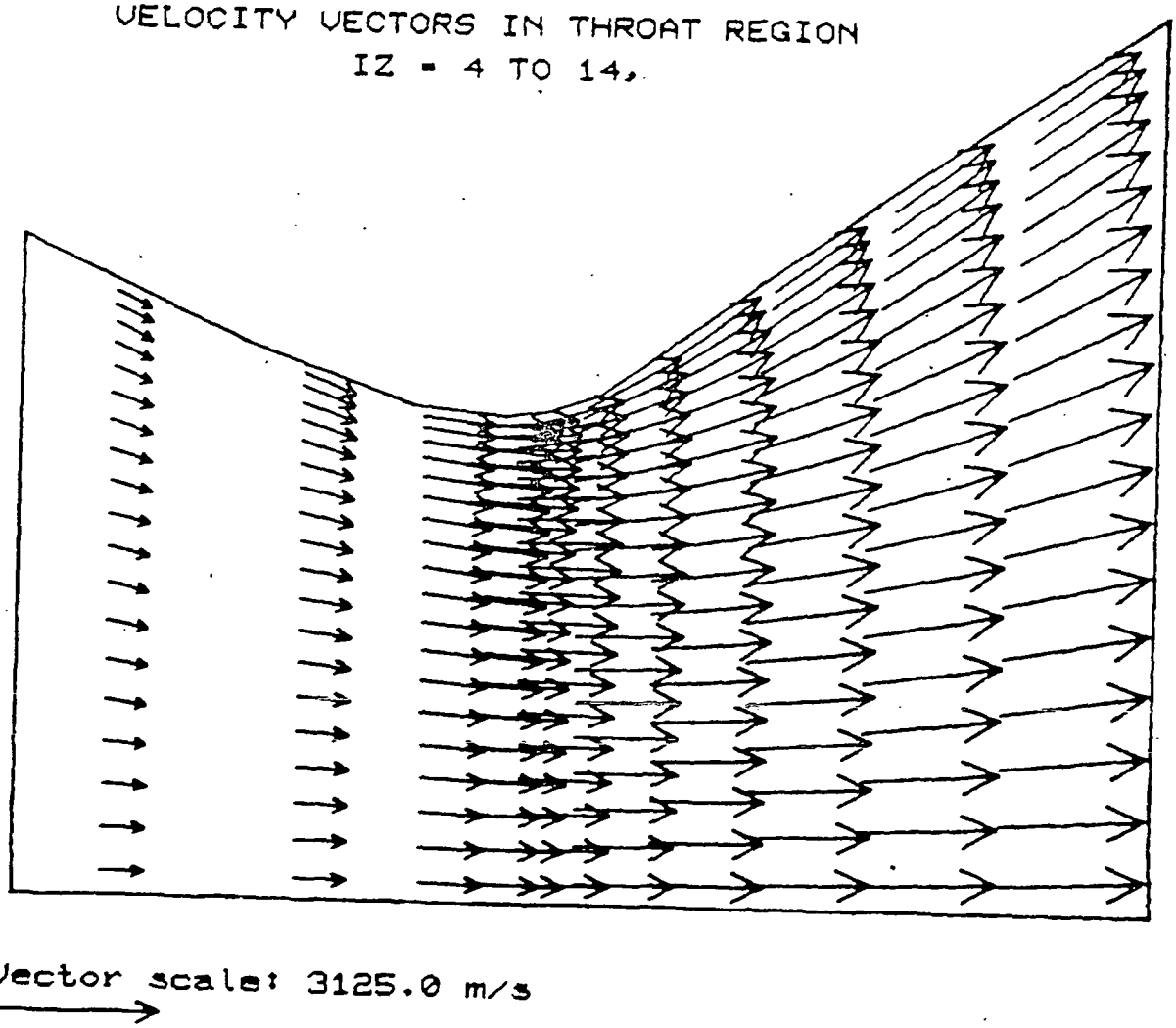

Figure 5.2 Details of Calculated Velocity Vectors Within the Throat Region

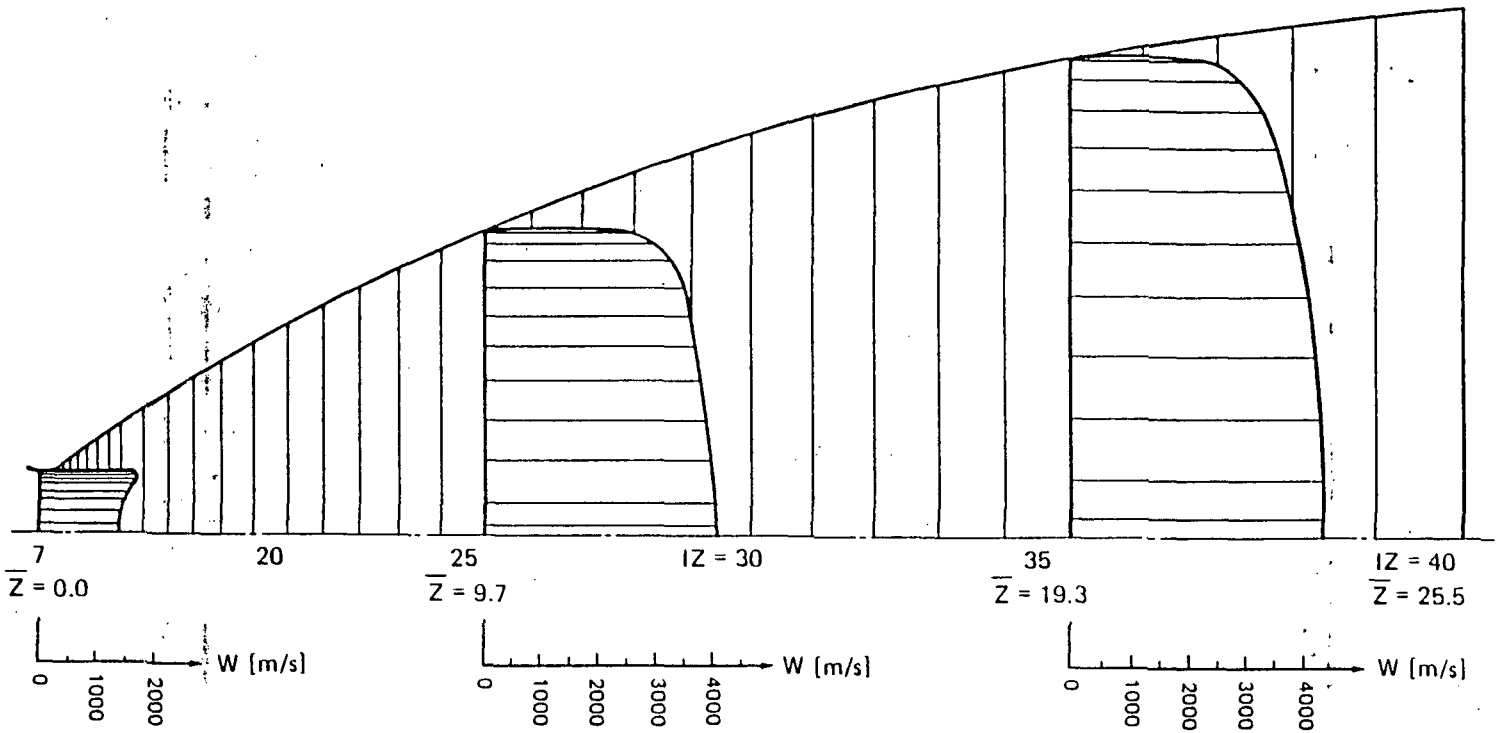

Figure 5.3 Axial Velocity Profiles at Selected SSME Nozzle Cross-Sections

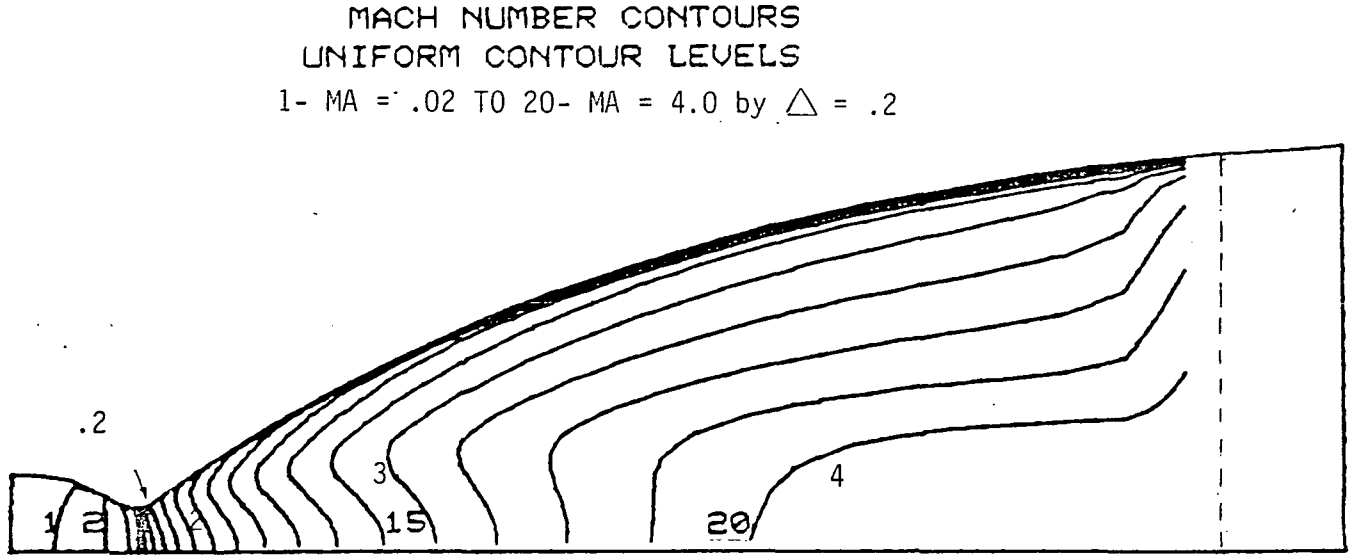

Figure 5.4 Calculated Mach Number Contours

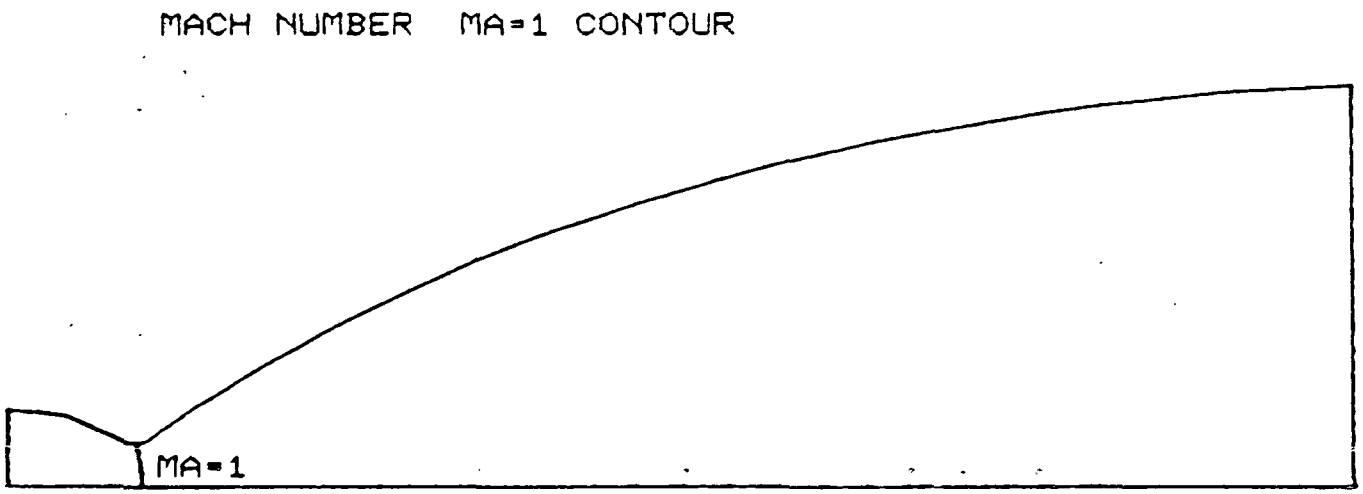

Figure 5.5 Location of Ma = 1

Range of values is 6406.92 to 0.202164E+08 [N/m^2]
Number of contours>20
values>10000 15000 20000 40000 60000
>80000 100000 150000 200000 400000
>600000 800000 1000000 2000000 4000000
>6000000 8000000 10000000 15000000 20000000

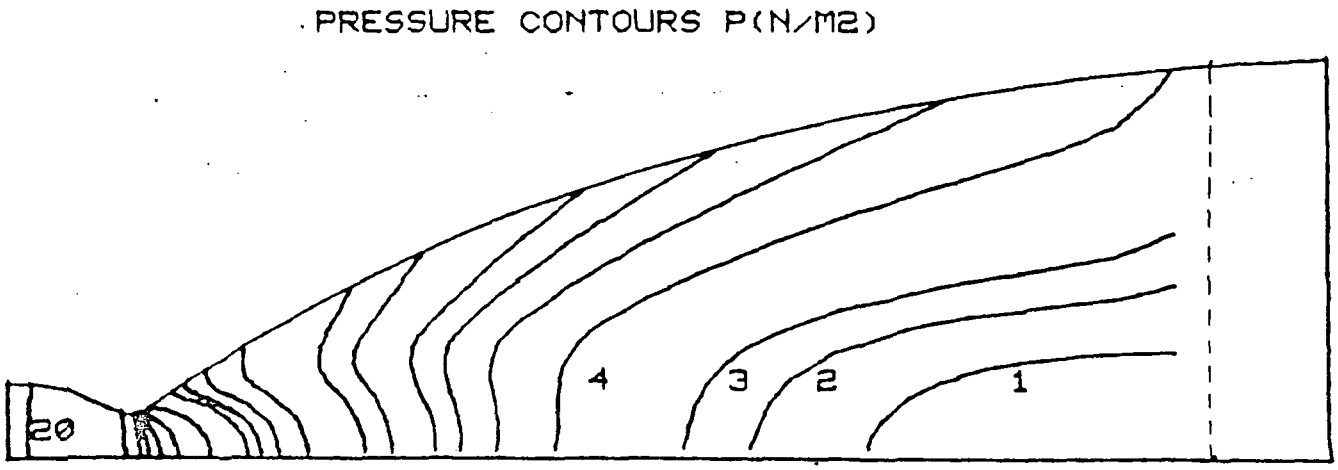

Figure 5.6 Calculated Pressure Contours

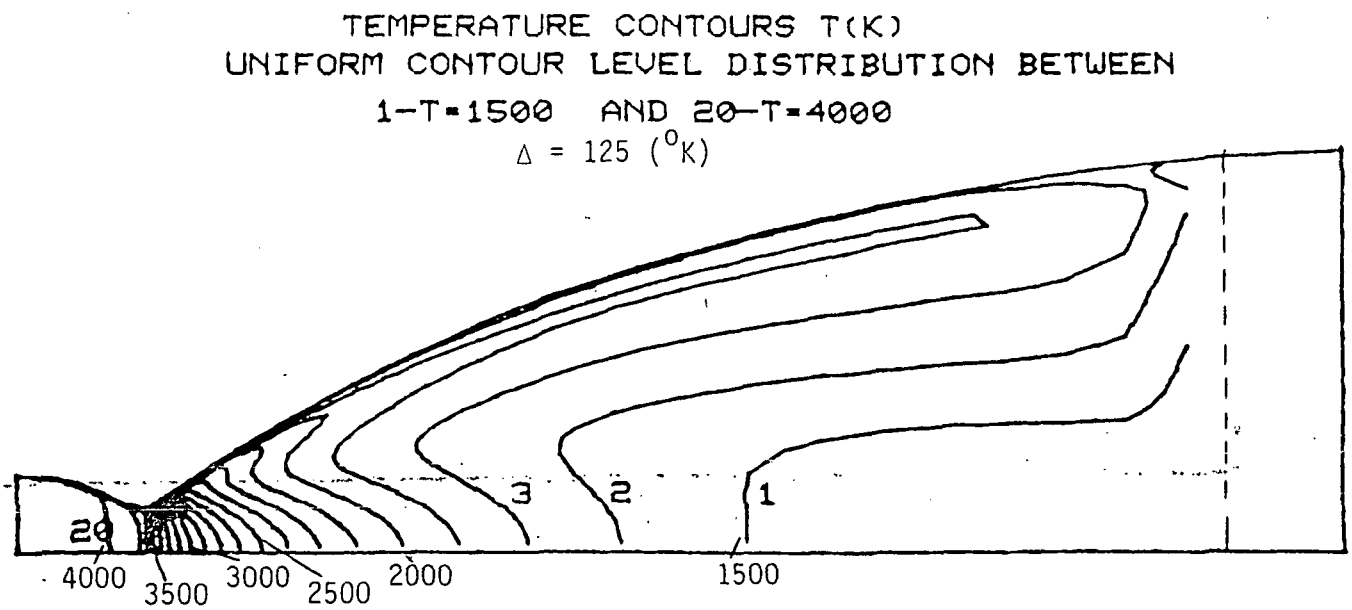

Figure 5.7 Calculated Temperature Contours

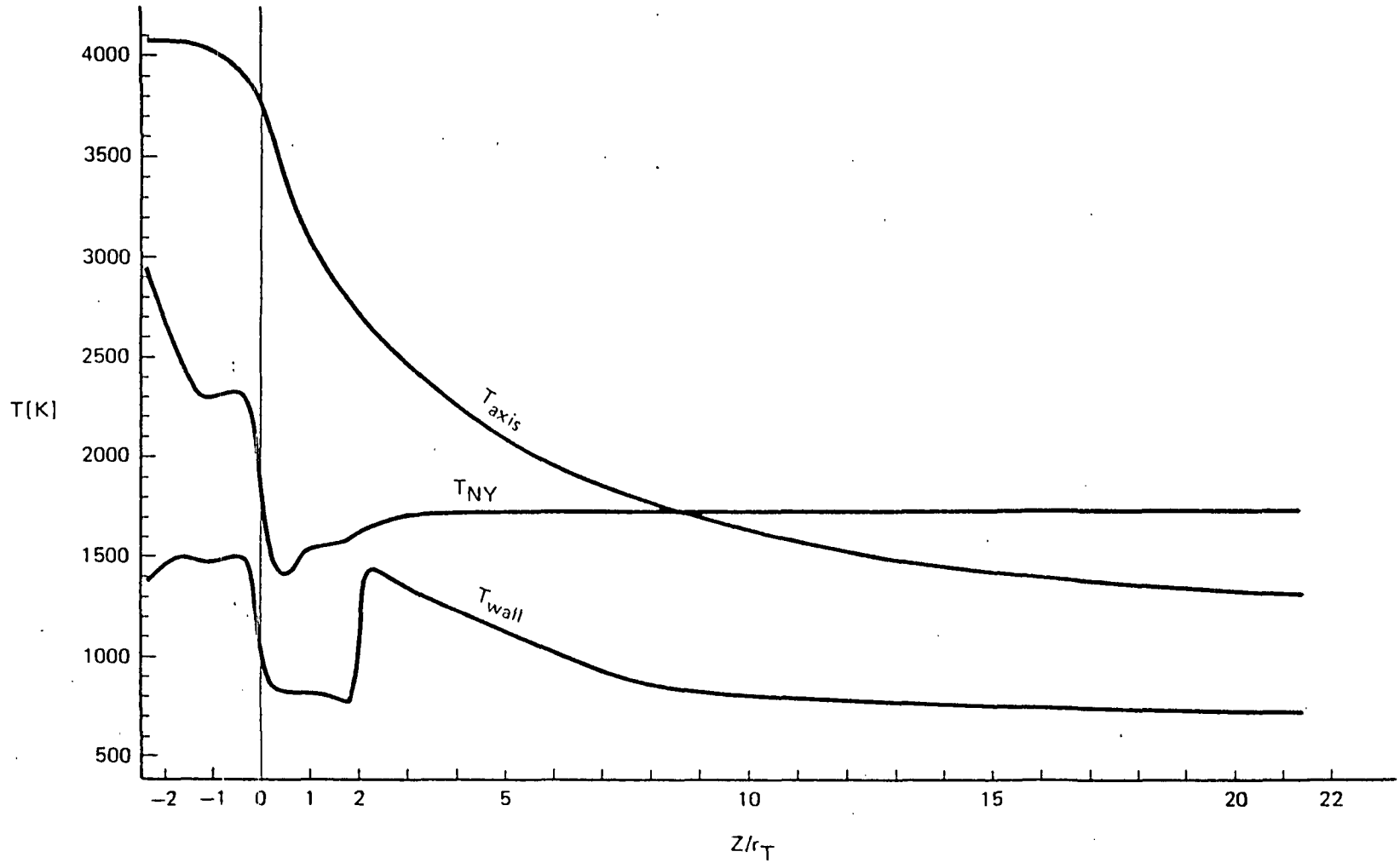

Figure 5.8 Axial Variations of Absolute Temperature at the Wall, at the "Near Wall" Grid Node Along the Axis of the Nozzle

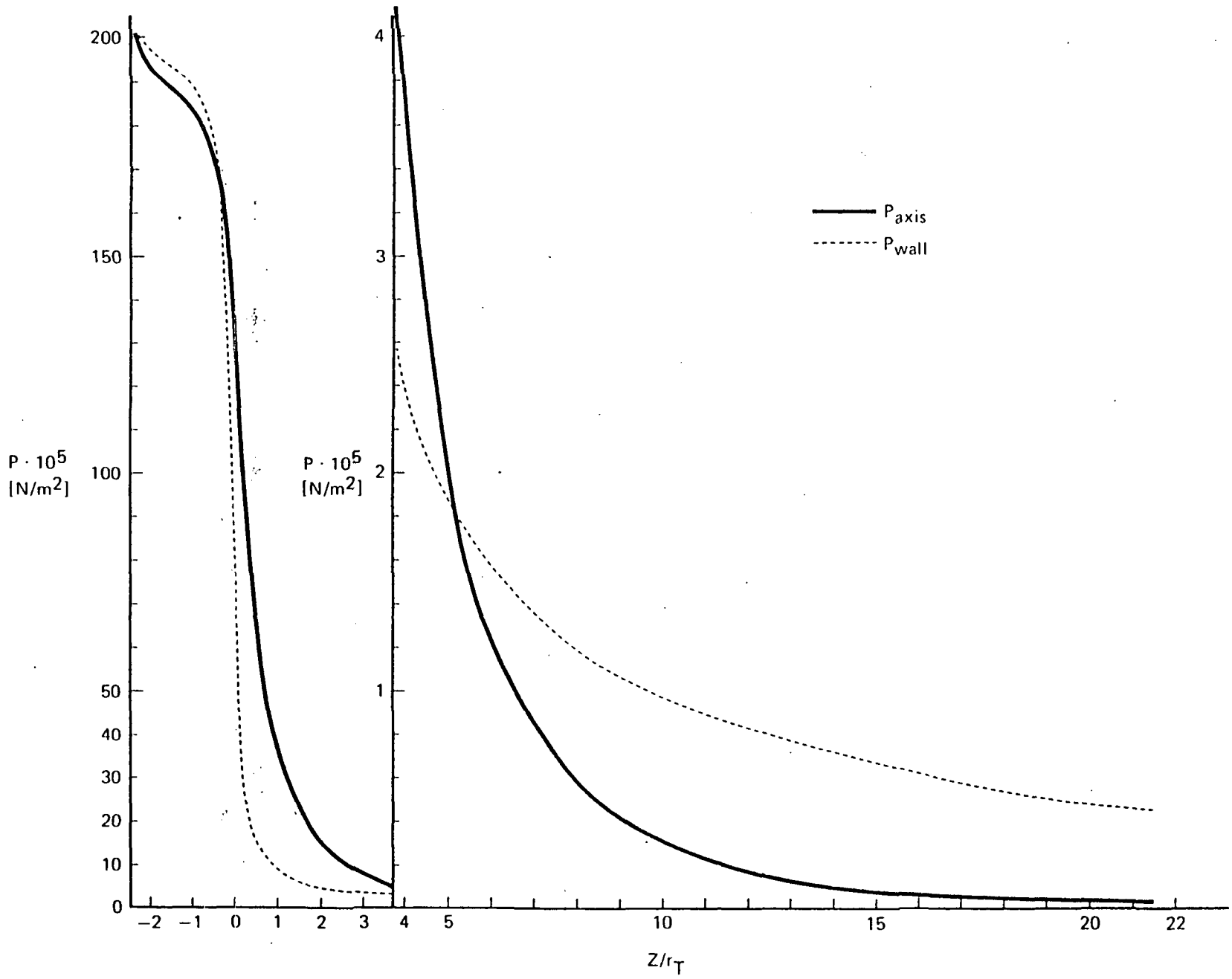

Figure 5.9 Axial Variations of Static Pressure at the "Near Wall" Grid Node and Along the Axis of the Nozzle

Table 1. Computer Printout Summary (S.I. Units)

********** OUTPUT SUMMARY **********

IZ	ZG	ZND	YN	ANG	PW	PAX	TW	TNY	TAX
1	4.2543E-02	-2.3920E+00	1.7016E+00	-7.2074E-05	2.0216E+07	2.0209E+07	1.3970E+03	2.9366E+03	4.0795E+03
2	1.2356E-01	-1.7729E+00	1.6989E+00	-3.9603E-03	1.9525E+07	1.9049E+07	1.5014E+03	2.4697E+03	4.0663E+03
3	1.9596E-01	-1.2198E+00	1.5656E+00	-7.6871E-03	1.9375E+07	1.8610E+07	1.4796E+03	2.2953E+03	4.0419E+03
4	2.5852E-01	-7.4175E-01	1.3256E+00	-7.7424E-03	1.8468E+07	1.7727E+07	1.4718E+03	2.3103E+03	4.0008E+03
5	3.0929E-01	-3.5388E-01	1.1212E+00	-6.1088E-03	1.6359E+07	1.6258E+07	1.4900E+03	2.3298E+03	3.9437E+03
6	3.4351E-01	-9.2435E-02	1.0000E+00	-1.6865E-03	1.1930E+07	1.4449E+07	1.3198E+03	2.1450E+03	3.8790E+03
7	3.5694E-01	1.0172E-02	9.8240E-01	4.6562E-04	8.8301E+06	1.2835E+07	1.1480E+03	1.9343E+03	3.8241E+03
8	3.6226E-01	5.0860E-02	9.8293E-01	2.2761E-03	6.6121E+06	1.1601E+07	1.0798E+03	1.7905E+03	3.7619E+03
9	3.7291E-01	1.3224E-01	9.9079E-01	6.0667E-03	4.2382E+06	1.0256E+07	9.4359E+02	1.6460E+03	3.6794E+03
10	3.8889E-01	2.5430E-01	1.0270E+00	1.0748E-02	2.2685E+06	8.9337E+06	8.3690E+02	1.4591E+03	3.5694E+03
11	4.1019E-01	4.1705E-01	1.1260E+00	1.1132E-02	1.6377E+06	7.4025E+06	8.2950E+02	1.4069E+03	3.4409E+03
12	4.3681E-01	6.2049E-01	1.2593E+00	1.0978E-02	1.2655E+06	5.8787E+06	8.2601E+02	1.4759E+03	3.3029E+03
13	4.6877E-01	8.6462E-01	1.4193E+00	1.0797E-02	9.9413E+05	4.4928E+06	8.2182E+02	1.5274E+03	3.1627E+03
14	5.0604E-01	1.1494E+00	1.6042E+00	1.0589E-02	7.9017E+05	3.3322E+06	8.1077E+02	1.5584E+03	3.0247E+03
15	5.4864E-01	1.4749E+00	1.8122E+00	1.0355E-02	6.3583E+05	2.4201E+06	7.9400E+02	1.5755E+03	2.8909E+03
16	5.9657E-01	1.8411E+00	2.0414E+00	1.0099E-02	5.1839E+05	1.7317E+06	7.6770E+02	1.5839E+03	2.7619E+03
17	6.4982E-01	2.2480E+00	2.2894E+00	9.8230E-03	4.2973E+05	1.2256E+06	1.4215E+03	1.6482E+03	2.6388E+03
18	7.0840E-01	2.6956E+00	2.5542E+00	9.5269E-03	3.5842E+05	8.6239E+05	1.3773E+03	1.6878E+03	2.5221E+03
19	7.7230E-01	3.1838E+00	2.8334E+00	9.2133E-03	3.0267E+05	6.0634E+05	1.3290E+03	1.7129E+03	2.4122E+03
20	8.4153E-01	3.7128E+00	3.1247E+00	8.8823E-03	2.5868E+05	4.2774E+05	1.2767E+03	1.7285E+03	2.3090E+03
21	9.1609E-01	4.2824E+00	3.4258E+00	8.5412E-03	2.2359E+05	3.0376E+05	1.2187E+03	1.7376E+03	2.2123E+03
22	9.9597E-01	4.8927E+00	3.7345E+00	8.1921E-03	1.9527E+05	2.1769E+05	1.1558E+03	1.7424E+03	2.1219E+03
23	1.0813E+00	5.5437E+00	4.0487E+00	7.8300E-03	1.7237E+05	1.5772E+05	1.0887E+03	1.7445E+03	2.0374E+03
24	1.1717E+00	6.2354E+00	4.3662E+00	7.4608E-03	1.5357E+05	1.1566E+05	1.0174E+03	1.7447E+03	1.9585E+03
25	1.2676E+00	6.9678E+00	4.6849E+00	7.0856E-03	1.3799E+05	8.5912E+04	9.4736E+02	1.7436E+03	1.8849E+03
26	1.3687E+00	7.7409E+00	5.0027E+00	6.7078E-03	1.2491E+05	6.4672E+04	8.9159E+02	1.7424E+03	1.8164E+03
27	1.4752E+00	8.5547E+00	5.3180E+00	6.3329E-03	1.1378E+05	4.9348E+04	8.5736E+02	1.7423E+03	1.7525E+03
28	1.5871E+00	9.4091E+00	5.6291E+00	5.9545E-03	1.0432E+05	3.8173E+04	8.3607E+02	1.7438E+03	1.6930E+03
29	1.7042E+00	1.0304E+01	5.9342E+00	5.5753E-03	9.6176E+04	2.9937E+04	8.1917E+02	1.7464E+03	1.6378E+03
30	1.8267E+00	1.1240E+01	6.2317E+00	5.1994E-03	8.9060E+04	2.3802E+04	8.0229E+02	1.7493E+03	1.5866E+03
31	1.9545E+00	1.2217E+01	6.5201E+00	4.8307E-03	8.2758E+04	1.9189E+04	7.8616E+02	1.7522E+03	1.5393E+03
32	2.0876E+00	1.3234E+01	6.7983E+00	4.4718E-03	7.7222E+04	1.5690E+04	7.7043E+02	1.7549E+03	1.4959E+03
33	2.2261E+00	1.4292E+01	7.0647E+00	4.1003E-03	7.2263E+04	1.3016E+04	7.5772E+02	1.7572E+03	1.4562E+03
34	2.3699E+00	1.5390E+01	7.3182E+00	3.7463E-03	6.7797E+04	1.0964E+04	7.4640E+02	1.7589E+03	1.4206E+03
35	2.5190E+00	1.6530E+01	7.5579E+00	3.3972E-03	6.3782E+04	9.3875E+03	7.3724E+02	1.7601E+03	1.3892E+03
36	2.6734E+00	1.7709E+01	7.7824E+00	3.0534E-03	6.0137E+04	8.1846E+03	7.2875E+02	1.7605E+03	1.3625E+03
37	2.8332E+00	1.8930E+01	7.9909E+00	2.7209E-03	5.6701E+04	7.2886E+03	7.2246E+02	1.7590E+03	1.3421E+03
38	2.9983E+00	2.0191E+01	8.1825E+00	2.3938E-03	5.3264E+04	6.6733E+03	7.1798E+02	1.7514E+03	1.3327E+03
39	3.1687E+00	2.1493E+01	8.3563E+00	2.0784E-03	4.8853E+04	6.4055E+03	7.1467E+02	1.7200E+03	1.3534E+03
40	3.3444E+00	2.2836E+01	8.5117E+00	1.7696E-03	3.9867E+04	6.8934E+03	7.1158E+02	1.5729E+03	1.4847E+03
41	3.6120E+00	2.4881E+01	8.6479E+00	8.8705E-04	1.1372E+04	1.0007E+04	7.1000E+02	1.6736E+03	1.4847E+03

Table 2. Computer Printout Summary (British Units)

OUTPUT SUMMARY IN BRITISH UNITS

IZ	ZG:TH	YN	PW(PSI)	PAX(PSI)	TW(R)	TNY(R)	TAX(R)
1	-2.3920E+00	1.7016E+00	2.9321E+03	2.9310E+03	2.5145E+03	5.2859E+03	7.3432E+03
2	-1.7729E+00	1.6989E+00	2.8318E+03	2.7628E+03	2.7024E+03	4.4454E+03	7.3194E+03
3	-1.2198E+00	1.5656E+00	2.8101E+03	2.6992E+03	2.6633E+03	4.1315E+03	7.2754E+03
4	-7.4175E-01	1.3256E+00	2.6786E+03	2.5711E+03	2.6492E+03	4.1585E+03	7.2014E+03
5	-3.5388E-01	1.1212E+00	2.3727E+03	2.3580E+03	2.6820E+03	4.1936E+03	7.0986E+03
6	-9.2435E-02	1.0000E+00	1.7303E+03	2.0957E+03	2.3756E+03	3.8610E+03	6.9822E+03
7	1.0172E-02	9.8240E-01	1.2807E+03	1.8616E+03	2.0663E+03	3.4818E+03	6.8833E+03
8	5.0860E-02	9.8293E-01	9.5901E+02	1.6826E+03	1.9437E+03	3.2229E+03	6.7713E+03
9	1.3224E-01	9.9079E-01	6.1469E+02	1.5021E+03	1.6985E+03	2.9629E+03	6.6230E+03
10	2.5430E-01	1.0270E+00	3.2902E+02	1.2957E+03	1.5064E+03	2.6264E+03	6.4249E+03
11	4.1705E-01	1.1260E+00	2.3752E+02	1.0736E+03	1.4931E+03	2.5324E+03	6.1935E+03
12	6.2049E-01	1.2593E+00	1.8355E+02	8.5263E+02	1.4868E+03	2.6566E+03	5.9458E+03
13	8.6462E-01	1.4193E+00	1.4419E+02	6.5163E+02	1.4793E+03	2.7493E+03	5.6929E+03
14	1.1494E+00	1.6042E+00	1.1460E+02	4.8330E+02	1.4594E+03	2.8051E+03	5.4445E+03
15	1.4749E+00	1.8122E+00	9.2219E+01	3.5101E+02	1.4292E+03	2.8359E+03	5.2036E+03
16	1.8411E+00	2.0414E+00	7.5186E+01	2.5116E+02	1.3819E+03	2.8510E+03	4.9714E+03
17	2.2480E+00	2.2894E+00	6.2327E+01	1.7775E+02	2.5588E+03	2.9667E+03	4.7498E+03
18	2.6956E+00	2.5542E+00	5.1984E+01	1.2508E+02	2.4791E+03	3.0380E+03	4.5399E+03
19	3.1838E+00	2.8334E+00	4.3896E+01	8.7942E+01	2.3922E+03	3.0833E+03	4.3420E+03
20	3.7128E+00	3.1247E+00	3.7518E+01	6.2038E+01	2.2980E+03	3.1113E+03	4.1562E+03
21	4.2824E+00	3.4258E+00	3.2429E+01	4.4057E+01	2.1936E+03	3.1277E+03	3.9822E+03
22	4.8927E+00	3.7345E+00	2.8322E+01	3.1574E+01	2.0804E+03	3.1363E+03	3.8193E+03
23	5.5437E+00	4.0487E+00	2.4999E+01	2.2875E+01	1.9597E+03	3.1401E+03	3.6672E+03
24	6.2354E+00	4.3662E+00	2.2273E+01	1.6775E+01	1.8313E+03	3.1404E+03	3.5253E+03
25	6.9678E+00	4.6849E+00	2.0013E+01	1.2461E+01	1.7052E+03	3.1384E+03	3.3929E+03
26	7.7409E+00	5.0027E+00	1.8117E+01	9.3799E+00	1.6049E+03	3.1364E+03	3.2694E+03
27	8.5547E+00	5.3180E+00	1.6503E+01	7.1573E+00	1.5433E+03	3.1362E+03	3.1544E+03
28	9.4091E+00	5.6291E+00	1.5130E+01	5.5365E+00	1.5049E+03	3.1389E+03	3.0475E+03
29	1.0304E+01	5.9342E+00	1.3949E+01	4.3419E+00	1.4745E+03	3.1435E+03	2.9481E+03
30	1.1240E+01	6.2317E+00	1.2917E+01	3.4523E+00	1.4441E+03	3.1487E+03	2.8559E+03
31	1.2217E+01	6.5201E+00	1.2003E+01	2.7832E+00	1.4151E+03	3.1539E+03	2.7708E+03
32	1.3234E+01	6.7983E+00	1.1200E+01	2.2756E+00	1.3868E+03	3.1588E+03	2.6925E+03
33	1.4292E+01	7.0647E+00	1.0481E+01	1.8879E+00	1.3639E+03	3.1629E+03	2.6212E+03
34	1.5390E+01	7.3182E+00	9.8331E+00	1.5902E+00	1.3435E+03	3.1660E+03	2.5571E+03
35	1.6530E+01	7.5579E+00	9.2508E+00	1.3615E+00	1.3270E+03	3.1683E+03	2.5005E+03
36	1.7709E+01	7.7824E+00	8.7221E+00	1.1871E+00	1.3117E+03	3.1688E+03	2.4525E+03
37	1.8930E+01	7.9909E+00	8.2238E+00	1.0571E+00	1.3004E+03	3.1661E+03	2.4159E+03
38	2.0191E+01	8.1825E+00	7.7252E+00	9.6788E-01	1.2924E+03	3.1525E+03	2.3989E+03
39	2.1493E+01	8.3563E+00	7.0856E+00	9.2904E-01	1.2864E+03	3.0959E+03	2.4361E+03
40	2.2836E+01	8.5117E+00	5.7821E+00	9.9981E-01	1.2808E+03	2.8313E+03	2.6724E+03
41	2.4881E+01	8.6479E+00	1.6494E+00	1.4514E+00	1.2780E+03	3.0124E+03	2.6725E+03

Table 3. Predicted Near-Wall and Axis Pressure Distributions (in Logarithmic Scale)

IZ	PW(PSIA)	PA(PSIA)	LOG(PW(PSIA))	LOG(PA(PSIA))
1	2.9321E+03	2.9310E+03	3.4672E+00	3.4670E+00
2	2.8318E+03	2.7628E+03	3.4521E+00	3.4413E+00
3	2.8191E+03	2.6992E+03	3.4501E+00	3.4312E+00
4	2.6786E+03	2.5711E+03	3.4279E+00	3.4101E+00
5	2.3727E+03	2.3580E+03	3.3752E+00	3.3725E+00
6	1.7303E+03	2.0957E+03	3.2381E+00	3.3213E+00
7	1.2807E+03	1.8616E+03	3.1074E+00	3.2699E+00
8	9.5901E+02	1.6826E+03	2.9818E+00	3.2260E+00
9	6.1469E+02	1.5021E+03	2.7887E+00	3.1767E+00
10	3.2902E+02	1.2957E+03	2.5172E+00	3.1125E+00
11	2.3752E+02	1.0736E+03	2.3757E+00	3.0308E+00
12	1.8355E+02	8.5263E+02	2.2638E+00	2.9308E+00
13	1.4419E+02	6.5163E+02	2.1589E+00	2.8140E+00
14	1.1460E+02	4.8330E+02	2.0592E+00	2.6842E+00
15	9.2219E+01	3.5101E+02	1.9648E+00	2.5453E+00
16	7.5186E+01	2.5116E+02	1.8761E+00	2.4000E+00
17	6.2327E+01	1.7775E+02	1.7947E+00	2.2498E+00
18	5.1984E+01	1.2508E+02	1.7159E+00	2.0972E+00
19	4.3898E+01	8.7942E+01	1.6424E+00	1.9442E+00
20	3.7518E+01	6.2038E+01	1.5742E+00	1.7927E+00
21	3.2429E+01	4.4057E+01	1.5109E+00	1.6440E+00
22	2.8322E+01	3.1574E+01	1.4521E+00	1.4993E+00
23	2.4999E+01	2.2875E+01	1.3979E+00	1.3594E+00
24	2.2273E+01	1.6775E+01	1.3478E+00	1.2247E+00
25	2.0013E+01	1.2461E+01	1.3013E+00	1.0956E+00
26	1.8117E+01	9.3799E+00	1.2581E+00	9.7220E-01
27	1.6503E+01	7.1573E+00	1.2176E+00	8.5475E-01
28	1.5130E+01	5.5365E+00	1.1798E+00	7.4324E-01
29	1.3949E+01	4.3419E+00	1.1445E+00	6.3768E-01
30	1.2917E+01	3.4523E+00	1.1112E+00	5.3811E-01
31	1.2003E+01	2.7832E+00	1.0793E+00	4.4454E-01
32	1.1200E+01	2.2756E+00	1.0492E+00	3.5710E-01
33	1.0481E+00	1.8879E+00	2.0403E-02	2.7598E-01
34	9.8331E+00	1.5902E+00	9.9269E-01	2.0145E-01
35	9.2508E+00	1.3615E+00	9.6618E-01	1.3402E-01
36	8.7221E+00	1.1871E+00	9.4062E-01	7.4487E-02
37	8.2238E+00	1.0571E+00	9.1507E-01	2.4116E-02
38	7.7252E+00	9.6788E-01	8.8791E-01	-1.4178E-02
39	7.0856E+00	9.2904E-01	8.5038E-01	-3.1966E-02
40	5.7821E+00	9.9981E-01	7.6209E-01	-8.2532E-05
41	1.6494E+00	1.4514E+00	2.1733E-01	1.6179E-01

Table 4. Predicted Wall Heat Transfer

HEAT TRANSFER TO THE WALL INFORMATION PRINTOUT

IZ	ZND	AREA	HTCOEF	TW-T(NY)	QFLX	QDOT	QSUM(1-IZ)
–	–	M2	W*M**-2K**-1	K	W*M**-2	W	W
1	3.251E-01	1.211E-01	2.378E+05	-1.540E+03	-3.662E+08	-4.434E+07	-4.434E+07
2	9.441E-01	1.079E-01	2.697E+05	-9.682E+02	-2.612E+08	-2.818E+07	-7.252E+07
3	1.497E+00	9.075E-02	2.671E+05	-8.157E+02	-2.179E+08	-1.977E+07	-9.230E+07
4	1.975E+00	6.496E-02	4.531E+05	-8.385E+02	-3.799E+08	-2.468E+07	-1.170E+08
5	2.363E+00	4.181E-02	6.433E+05	-8.398E+02	-5.403E+08	-2.259E+07	-1.396E+08
6	2.625E+00	2.017E-02	8.690E+05	-8.253E+02	-7.171E+08	-1.446E+07	-1.540E+08
7	2.727E+00	2.191E-03	4.385E+06	-7.864E+02	-3.448E+09	-7.554E+06	-1.616E+08
8	2.768E+00	6.655E-03	1.177E+06	-7.107E+02	-8.362E+08	-5.565E+06	-1.671E+08
9	2.849E+00	1.196E-02	6.597E+05	-7.025E+02	-4.635E+08	-5.542E+06	-1.727E+08
10	2.971E+00	2.057E-02	3.050E+05	-6.223E+02	-1.898E+08	-3.905E+06	-1.766E+08
11	3.134E+00	2.978E-02	1.157E+05	-5.776E+02	-6.681E+07	-1.989E+06	-1.786E+08
12	3.338E+00	4.061E-02	7.207E+04	-6.501E+02	-4.685E+07	-1.902E+06	-1.805E+08
13	3.582E+00	5.377E-02	5.214E+04	-7.059E+02	-3.681E+07	-1.979E+06	-1.825E+08
14	3.866E+00	6.951E-02	3.978E+04	-7.481E+02	-2.976E+07	-2.069E+06	-1.845E+08
15	4.192E+00	8.806E-02	3.131E+04	-7.822E+02	-2.449E+07	-2.156E+06	-1.867E+08
16	4.558E+00	1.095E-01	2.515E+04	-8.170E+02	-2.055E+07	-2.251E+06	-1.889E+08
17	4.965E+00	1.340E-01	2.056E+04	-2.276E+02	-4.680E+06	-6.273E+05	-1.896E+08
18	5.413E+00	1.616E-01	1.712E+04	-3.116E+02	-5.334E+06	-8.618E+05	-1.904E+08
19	5.901E+00	1.921E-01	1.437E+04	-3.851E+02	-5.535E+06	-1.064E+06	-1.915E+08
20	6.430E+00	2.257E-01	1.224E+04	-4.530E+02	-5.546E+06	-1.252E+06	-1.927E+08
21	6.999E+00	2.622E-01	1.057E+04	-5.201E+02	-5.497E+06	-1.441E+06	-1.942E+08
22	7.610E+00	3.015E-01	9.223E+03	-5.878E+02	-5.421E+06	-1.635E+06	-1.958E+08
23	8.261E+00	3.435E-01	8.133E+03	-6.570E+02	-5.343E+06	-1.835E+06	-1.977E+08
24	8.952E+00	3.879E-01	7.246E+03	-7.284E+02	-5.277E+06	-2.047E+06	-1.997E+08
25	9.685E+00	4.348E-01	6.513E+03	-7.973E+02	-5.193E+06	-2.258E+06	-2.020E+08
26	1.046E+01	4.839E-01	5.903E+03	-8.518E+02	-5.028E+06	-2.433E+06	-2.044E+08
27	1.127E+01	5.350E-01	5.381E+03	-8.858E+02	-4.766E+06	-2.550E+06	-2.069E+08
28	1.213E+01	5.880E-01	4.930E+03	-9.085E+02	-4.479E+06	-2.633E+06	-2.096E+08
29	1.302E+01	6.426E-01	4.544E+03	-9.279E+02	-4.216E+06	-2.709E+06	-2.123E+08
30	1.396E+01	6.987E-01	4.210E+03	-9.476E+02	-3.989E+06	-2.787E+06	-2.151E+08
31	1.493E+01	7.560E-01	3.911E+03	-9.666E+02	-3.781E+06	-2.858E+06	-2.179E+08
32	1.595E+01	8.144E-01	3.647E+03	-9.850E+02	-3.593E+06	-2.926E+06	-2.209E+08
33	1.701E+01	8.735E-01	3.414E+03	-1.000E+03	-3.414E+06	-2.982E+06	-2.238E+08
34	1.811E+01	9.332E-01	3.203E+03	-1.013E+03	-3.245E+06	-3.028E+06	-2.269E+08
35	1.925E+01	9.932E-01	3.012E+03	-1.023E+03	-3.083E+06	-3.062E+06	-2.299E+08
36	2.043E+01	1.053E+00	2.846E+03	-1.032E+03	-2.938E+06	-3.094E+06	-2.330E+08
37	2.165E+01	1.113E+00	2.705E+03	-1.037E+03	-2.805E+06	-3.122E+06	-2.361E+08
38	2.291E+01	1.172E+00	2.620E+03	-1.034E+03	-2.708E+06	-3.175E+06	-2.393E+08
39	2.421E+01	1.231E+00	2.706E+03	-1.006E+03	-2.721E+06	-3.348E+06	-2.427E+08
40	2.555E+01	1.288E+00	3.393E+03	-8.617E+02	-2.924E+06	-3.766E+06	-2.464E+08
41	2.760E+01	2.607E+00	1.829E+03	-9.640E+02	-1.763E+06	-4.596E+06	-2.510E+08

Table 5. Computer Printout for Cartesian Component of Axial Velocity

throat

FIELD VALUES OF WCRT

IY=20	1,800E+02	2,067E+02	2,370E+02	4,592E+02	8,523E+02	1,118E+03	1,238E+03	1,313E+03	1,173E+03
IY=18	3,059E+02	3,387E+02	4,920E+02	7,874E+02	1,218E+03	1,472E+03	1,727E+03	1,943E+03	2,006E+03
IY=16	3,126E+02	3,607E+02	5,348E+02	8,309E+02	1,201E+03	1,460E+03	1,699E+03	1,952E+03	2,148E+03
IY=14	3,220E+02	3,846E+02	5,605E+02	8,391E+02	1,160E+03	1,410E+03	1,627E+03	1,869E+03	2,126E+03
IY=12	3,338E+02	4,103E+02	5,853E+02	8,455E+02	1,132E+03	1,372E+03	1,571E+03	1,792E+03	2,056E+03
IY=10	3,463E+02	4,354E+02	6,076E+02	8,506E+02	1,114E+03	1,344E+03	1,528E+03	1,730E+03	1,980E+03
IY= 8	3,589E+02	4,578E+02	6,263E+02	8,549E+02	1,101E+03	1,323E+03	1,496E+03	1,680E+03	1,911E+03
IY= 6	3,696E+02	4,763E+02	6,409E+02	8,583E+02	1,093E+03	1,308E+03	1,471E+03	1,642E+03	1,853E+03
IY= 4	3,781E+02	4,898E+02	6,513E+02	8,607E+02	1,088E+03	1,297E+03	1,454E+03	1,615E+03	1,810E+03
IY= 2	3,834E+02	4,978E+02	6,573E+02	8,623E+02	1,085E+03	1,291E+03	1,443E+03	1,599E+03	1,784E+03
IZ=	1	2	3	4	5	6	7	8	9
IY=20	8,514E+02	8,728E+02	1,045E+03	1,208E+03	1,354E+03	1,485E+03	1,605E+03	1,701E+03	1,796E+03
IY=18	1,795E+03	1,752E+03	1,846E+03	1,969E+03	2,091E+03	2,206E+03	2,314E+03	2,419E+03	2,516E+03
IY=16	2,111E+03	2,043E+03	2,062E+03	2,159E+03	2,283E+03	2,407E+03	2,525E+03	2,636E+03	2,741E+03
IY=14	2,249E+03	2,258E+03	2,264E+03	2,306E+03	2,396E+03	2,508E+03	2,624E+03	2,737E+03	2,844E+03
IY=12	2,263E+03	2,369E+03	2,426E+03	2,474E+03	2,535E+03	2,620E+03	2,720E+03	2,825E+03	2,930E+03
IY=10	2,224E+03	2,398E+03	2,514E+03	2,601E+03	2,676E+03	2,755E+03	2,841E+03	2,934E+03	3,029E+03
IY= 8	2,164E+03	2,375E+03	2,537E+03	2,666E+03	2,776E+03	2,873E+03	2,966E+03	3,057E+03	3,147E+03
IY= 6	2,097E+03	2,324E+03	2,518E+03	2,682E+03	2,823E+03	2,947E+03	3,059E+03	3,162E+03	3,258E+03
IY= 4	2,041E+03	2,270E+03	2,480E+03	2,667E+03	2,832E+03	2,980E+03	3,112E+03	3,230E+03	3,338E+03
IY= 2	2,004E+03	2,230E+03	2,447E+03	2,646E+03	2,825E+03	2,987E+03	3,132E+03	3,264E+03	3,382E+03
IZ=	10	11	12	13	14	15	16	17	18
IY=20	1,889E+03	1,979E+03	2,064E+03	2,143E+03	2,217E+03	2,285E+03	2,347E+03	2,404E+03	2,453E+03
IY=18	2,607E+03	2,694E+03	2,777E+03	2,856E+03	2,930E+03	3,000E+03	3,067E+03	3,129E+03	3,187E+03
IY=16	2,839E+03	2,932E+03	3,018E+03	3,100E+03	3,176E+03	3,249E+03	3,316E+03	3,380E+03	3,440E+03
IY=14	2,945E+03	3,039E+03	3,127E+03	3,210E+03	3,287E+03	3,360E+03	3,428E+03	3,491E+03	3,551E+03
IY=12	3,030E+03	3,126E+03	3,215E+03	3,299E+03	3,378E+03	3,451E+03	3,519E+03	3,583E+03	3,643E+03
IY=10	3,123E+03	3,214E+03	3,301E+03	3,384E+03	3,462E+03	3,536E+03	3,604E+03	3,668E+03	3,728E+03
IY= 8	3,239E+03	3,321E+03	3,403E+03	3,482E+03	3,557E+03	3,627E+03	3,693E+03	3,756E+03	3,814E+03
IY= 6	3,348E+03	3,434E+03	3,514E+03	3,590E+03	3,662E+03	3,729E+03	3,792E+03	3,851E+03	3,906E+03
IY= 4	3,437E+03	3,527E+03	3,610E+03	3,688E+03	3,759E+03	3,825E+03	3,887E+03	3,944E+03	3,996E+03
IY= 2	3,489E+03	3,586E+03	3,674E+03	3,755E+03	3,828E+03	3,895E+03	3,956E+03	4,013E+03	4,064E+03
IZ=	19	20	21	22	23	24	25	26	27
IY=20	2,498E+03	2,537E+03	2,571E+03	2,599E+03	2,623E+03	2,642E+03	2,656E+03	2,667E+03	2,675E+03
IY=18	3,241E+03	3,291E+03	3,336E+03	3,377E+03	3,414E+03	3,447E+03	3,475E+03	3,499E+03	3,519E+03
IY=16	3,495E+03	3,547E+03	3,595E+03	3,639E+03	3,680E+03	3,717E+03	3,750E+03	3,781E+03	3,808E+03
IY=14	3,606E+03	3,657E+03	3,704E+03	3,748E+03	3,787E+03	3,823E+03	3,856E+03	3,885E+03	3,911E+03
IY=12	3,698E+03	3,748E+03	3,795E+03	3,838E+03	3,876E+03	3,911E+03	3,942E+03	3,970E+03	3,994E+03
IY=10	3,783E+03	3,834E+03	3,880E+03	3,922E+03	3,960E+03	3,993E+03	4,023E+03	4,049E+03	4,070E+03
IY= 8	3,868E+03	3,918E+03	3,964E+03	4,005E+03	4,042E+03	4,075E+03	4,104E+03	4,127E+03	4,147E+03
IY= 6	3,958E+03	4,005E+03	4,049E+03	4,089E+03	4,126E+03	4,158E+03	4,185E+03	4,209E+03	4,227E+03
IY= 4	4,045E+03	4,090E+03	4,131E+03	4,169E+03	4,204E+03	4,235E+03	4,262E+03	4,285E+03	4,304E+03
IY= 2	4,118E+03	4,155E+03	4,194E+03	4,231E+03	4,263E+03	4,293E+03	4,319E+03	4,342E+03	4,361E+03
IZ=	28	29	30	31	32	33	34	35	36
IY=20	2,682E+03	2,693E+03	2,723E+03	2,866E+03					
IY=18	3,539E+03	3,553E+03	3,596E+03	3,754E+03					
IY=16	3,834E+03	3,863E+03	3,915E+03	4,076E+03					
IY=14	3,939E+03	3,962E+03	4,009E+03	4,157E+03					
IY=12	4,019E+03	4,039E+03	4,081E+03	4,211E+03					
IY=10	4,089E+03	4,109E+03	4,144E+03	4,252E+03					
IY= 8	4,163E+03	4,178E+03	4,203E+03	4,284E+03					
IY= 6	4,240E+03	4,250E+03	4,263E+03	4,303E+03					
IY= 4	4,318E+03	4,325E+03	4,323E+03	4,305E+03					
IY= 2	4,376E+03	4,383E+03	4,372E+03	4,295E+03					
IZ=	37	38	39	40					

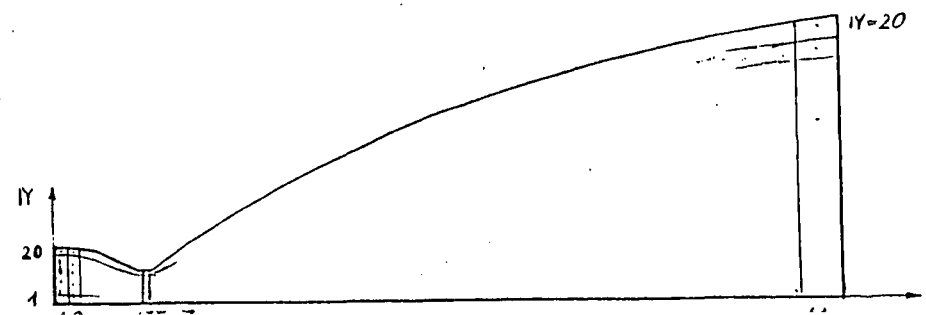

Table 6. Computer Printout for Cartesian Component of Radial Velocity

FIELD VALUES OF VCRT

IY=20	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
IY=18	-2.330E+00	-7.617E+01	-2.239E+02	-3.526E+02	-4.107E+02	-1.561E+02	-1.008E+02	1.050E+02	4.823E+02	9.585E+02
IY=16	-1.806E+00	-8.087E+01	-2.237E+02	-3.363E+02	-3.558E+02	-1.833E+02	-1.566E+02	-3.736E+01	2.484E+02	7.081E+02
IY=14	-1.573E+00	-8.336E+01	-2.092E+02	-2.983E+02	-2.974E+02	-1.893E+02	-1.737E+02	-1.042E+02	8.048E+01	4.465E+02
IY=12	-1.468E+00	-8.272E+01	-1.892E+02	-2.564E+02	-2.470E+02	-1.799E+02	-1.703E+02	-1.270E+02	-9.710E+00	2.549E+02
IY=10	-1.319E+00	-7.803E+01	-1.645E+02	-2.135E+02	-2.022E+02	-1.603E+02	-1.542E+02	-1.261E+02	-5.080E+01	1.311E+02
IY= 8	-1.121E+00	-6.900E+01	-1.361E+02	-1.707E+02	-1.607E+02	-1.342E+02	-1.302E+02	-1.116E+02	-6.253E+01	5.857E+01
IY= 6	-8.778E-01	-5.598E+01	-1.050E+02	-1.283E+02	-1.207E+02	-1.040E+02	-1.014E+02	-8.909E+01	-5.712E+01	2.108E+01
IY= 4	-6.044E-01	-3.961E+01	-7.169E+01	-8.616E+01	-8.110E+01	-7.119E+01	-6.955E+01	-6.186E+01	-4.214E+01	5.288E+00
IY= 2	-3.026E-01	-2.070E+01	-3.668E+01	-4.366E+01	-4.113E+01	-3.642E+01	-3.563E+01	-3.185E+01	-2.221E+01	9.010E-01
IZ=	1	2	3	4	5	6	7	8	9	10
IY=20	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
IY=18	1.228E+03	1.334E+03	1.398E+03	1.446E+03	1.482E+03	1.505E+03	1.512E+03	1.513E+03	1.506E+03	1.489E+03
IY=16	1.123E+03	1.383E+03	1.507E+03	1.572E+03	1.612E+03	1.636E+03	1.644E+03	1.640E+03	1.628E+03	1.606E+03
IY=14	8.546E+02	1.210E+03	1.453E+03	1.586E+03	1.653E+03	1.685E+03	1.695E+03	1.689E+03	1.672E+03	1.646E+03
IY=12	5.964E+02	9.427E+02	1.245E+03	1.466E+03	1.601E+03	1.674E+03	1.705E+03	1.710E+03	1.695E+03	1.668E+03
IY=10	3.949E+02	6.893E+02	9.739E+02	1.225E+03	1.411E+03	1.537E+03	1.612E+03	1.649E+03	1.658E+03	1.646E+03
IY= 8	2.507E+02	4.816E+02	7.192E+02	9.404E+02	1.133E+03	1.281E+03	1.386E+03	1.455E+03	1.493E+03	1.508E+03
IY= 6	1.530E+02	3.205E+02	5.005E+02	6.743E+02	8.334E+02	9.674E+02	1.073E+03	1.151E+03	1.205E+03	1.237E+03
IY= 4	8.797E+01	1.964E+02	3.162E+02	4.344E+02	5.429E+02	6.407E+02	7.235E+02	7.898E+02	8.400E+02	8.751E+02
IY= 2	4.166E+01	9.550E+01	1.553E+02	2.146E+02	2.692E+02	3.192E+02	3.645E+02	4.032E+02	4.345E+02	4.581E+02
IZ=	11	12	13	14	15	16	17	18	19	20
IY=20	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
IY=18	1.469E+03	1.435E+03	1.397E+03	1.354E+03	1.306E+03	1.253E+03	1.197E+03	1.137E+03	1.074E+03	1.009E+03
IY=16	1.577E+03	1.540E+03	1.497E+03	1.448E+03	1.393E+03	1.334E+03	1.271E+03	1.205E+03	1.136E+03	1.064E+03
IY=14	1.612E+03	1.571E+03	1.524E+03	1.471E+03	1.413E+03	1.350E+03	1.283E+03	1.213E+03	1.140E+03	1.064E+03
IY=12	1.630E+03	1.585E+03	1.534E+03	1.477E+03	1.416E+03	1.350E+03	1.280E+03	1.207E+03	1.131E+03	1.052E+03
IY=10	1.618E+03	1.578E+03	1.529E+03	1.472E+03	1.410E+03	1.342E+03	1.270E+03	1.195E+03	1.116E+03	1.034E+03
IY= 8	1.503E+03	1.484E+03	1.452E+03	1.410E+03	1.360E+03	1.302E+03	1.238E+03	1.168E+03	1.093E+03	1.013E+03
IY= 6	1.252E+03	1.253E+03	1.242E+03	1.220E+03	1.190E+03	1.152E+03	1.107E+03	1.057E+03	1.000E+03	9.378E+02
IY= 4	8.971E+02	9.077E+02	9.085E+02	9.009E+02	8.863E+02	8.656E+02	8.396E+02	8.088E+02	7.737E+02	7.345E+02
IY= 2	4.743E+02	4.839E+02	4.876E+02	4.862E+02	4.804E+02	4.711E+02	4.586E+02	4.435E+02	4.260E+02	4.065E+02
IZ=	21	22	23	24	25	26	27	28	29	30
IY=20	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
IY=18	9.431E+02	8.755E+02	8.071E+02	7.385E+02	6.699E+02	6.015E+02	5.342E+02	4.688E+02	4.077E+02	3.600E+02
IY=16	9.910E+02	9.167E+02	8.418E+02	7.666E+02	6.916E+02	6.172E+02	5.438E+02	4.725E+02	4.057E+02	3.531E+02
IY=14	9.870E+02	9.081E+02	8.284E+02	7.484E+02	6.686E+02	5.896E+02	5.119E+02	4.363E+02	3.656E+02	3.092E+02
IY=12	9.704E+02	8.875E+02	8.034E+02	7.188E+02	6.342E+02	5.503E+02	4.679E+02	3.880E+02	3.134E+02	2.537E+02
IY=10	9.491E+02	8.624E+02	7.742E+02	6.850E+02	5.955E+02	5.064E+02	4.186E+02	3.338E+02	2.548E+02	1.920E+02
IY= 8	9.290E+02	8.414E+02	7.508E+02	6.578E+02	5.633E+02	4.683E+02	3.740E+02	2.828E+02	1.979E+02	1.310E+02
IY= 6	8.699E+02	7.965E+02	7.174E+02	6.328E+02	5.430E+02	4.487E+02	3.510E+02	2.521E+02	1.588E+02	8.536E+01
IY= 4	6.911E+02	6.435E+02	5.914E+02	5.342E+02	4.712E+02	4.018E+02	3.253E+02	2.418E+02	1.539E+02	7.863E+01
IY= 2	3.891E+02	3.617E+02	3.362E+02	3.085E+02	2.780E+02	2.442E+02	2.064E+02	1.636E+02	1.163E+02	7.168E+01
IZ=	31	32	33	34	35	36	37	38	39	40
IY=20	0.000E+00									
IY=18	3.605E+02									
IY=16	3.479E+02									
IY=14	3.038E+02									
IY=12	2.481E+02									
IY=10	1.864E+02									
IY= 8	1.254E+02									
IY= 6	7.988E+01									
IY= 4	7.128E+01									
IY= 2	6.506E+01									
IZ=	41									

throat

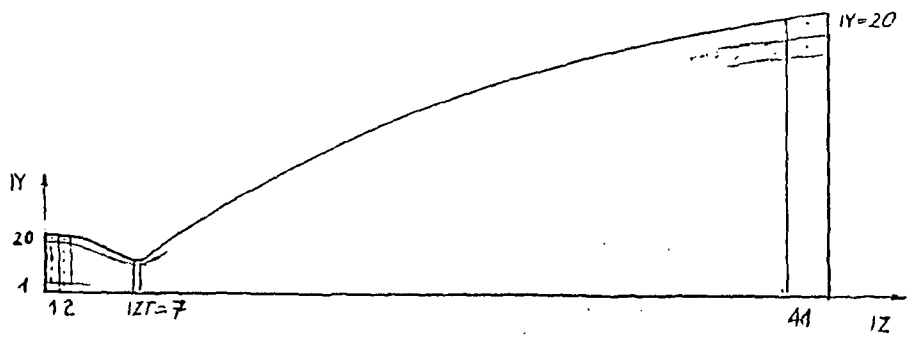

Table 7. Computer Printout for Absolute Temperature

throat

FIELD VALUES OF TEMP

IY=20	2,936E+03	2,470E+03	2,295E+03	2,310E+03	2,330E+03	2,145E+03	1,936E+03	1,793E+03	1,648E+03	1,461E+03
IY=18	4,075E+03	4,048E+03	3,861E+03	3,720E+03	3,586E+03	3,483E+03	3,366E+03	3,213E+03	2,993E+03	2,677E+03
IY=16	4,086E+03	4,080E+03	4,048E+03	3,978E+03	3,875E+03	3,799E+03	3,709E+03	3,589E+03	3,420E+03	3,145E+03
IY=14	4,085E+03	4,078E+03	4,046E+03	3,983E+03	3,898E+03	3,827E+03	3,752E+03	3,665E+03	3,566E+03	3,370E+03
IY=12	4,084E+03	4,075E+03	4,044E+03	3,987E+03	3,913E+03	3,842E+03	3,775E+03	3,698E+03	3,616E+03	3,467E+03
IY=10	4,083E+03	4,073E+03	4,043E+03	3,992E+03	3,924E+03	3,854E+03	3,792E+03	3,721E+03	3,642E+03	3,513E+03
IY= 8	4,082E+03	4,070E+03	4,043E+03	3,995E+03	3,932E+03	3,863E+03	3,804E+03	3,737E+03	3,658E+03	3,537E+03
IY= 6	4,081E+03	4,068E+03	4,042E+03	3,998E+03	3,937E+03	3,870E+03	3,813E+03	3,748E+03	3,668E+03	3,552E+03
IY= 4	4,080E+03	4,067E+03	4,042E+03	3,999E+03	3,941E+03	3,875E+03	3,819E+03	3,756E+03	3,675E+03	3,562E+03
IY= 2	4,080E+03	4,066E+03	4,042E+03	4,000E+03	3,943E+03	3,878E+03	3,823E+03	3,761E+03	3,679E+03	3,568E+03
IZ=	1	2	3	4	5	6	7	8	9	10
IY=20	1,408E+03	1,476E+03	1,528E+03	1,559E+03	1,576E+03	1,585E+03	1,649E+03	1,689E+03	1,714E+03	1,729E+03
IY=18	2,460E+03	2,329E+03	2,239E+03	2,164E+03	2,101E+03	2,047E+03	2,001E+03	1,960E+03	1,927E+03	1,900E+03
IY=16	2,867E+03	2,666E+03	2,531E+03	2,427E+03	2,339E+03	2,262E+03	2,195E+03	2,137E+03	2,086E+03	2,043E+03
IY=14	3,115E+03	2,869E+03	2,663E+03	2,507E+03	2,385E+03	2,285E+03	2,201E+03	2,129E+03	2,069E+03	2,018E+03
IY=12	3,292E+03	3,020E+03	2,790E+03	2,587E+03	2,420E+03	2,287E+03	2,180E+03	2,094E+03	2,024E+03	1,967E+03
IY=10	3,327E+03	3,122E+03	2,908E+03	2,697E+03	2,507E+03	2,345E+03	2,210E+03	2,100E+03	2,011E+03	1,939E+03
IY= 8	3,372E+03	3,190E+03	3,001E+03	2,809E+03	2,624E+03	2,455E+03	2,307E+03	2,179E+03	2,071E+03	1,980E+03
IY= 6	3,402E+03	3,238E+03	3,069E+03	2,899E+03	2,733E+03	2,575E+03	2,431E+03	2,300E+03	2,184E+03	2,082E+03
IY= 4	3,424E+03	3,274E+03	3,120E+03	2,968E+03	2,819E+03	2,677E+03	2,542E+03	2,417E+03	2,302E+03	2,198E+03
IY= 2	3,438E+03	3,297E+03	3,154E+03	3,013E+03	2,876E+03	2,744E+03	2,619E+03	2,501E+03	2,390E+03	2,286E+03
IZ=	11	12	13	14	15	16	17	18	19	20
IY=20	1,739E+03	1,743E+03	1,746E+03	1,746E+03	1,744E+03	1,743E+03	1,743E+03	1,744E+03	1,747E+03	1,750E+03
IY=18	1,878E+03	1,862E+03	1,851E+03	1,843E+03	1,838E+03	1,836E+03	1,835E+03	1,835E+03	1,836E+03	1,836E+03
IY=16	2,007E+03	1,979E+03	1,956E+03	1,938E+03	1,925E+03	1,916E+03	1,909E+03	1,905E+03	1,903E+03	1,902E+03
IY=14	1,976E+03	1,941E+03	1,914E+03	1,892E+03	1,875E+03	1,863E+03	1,855E+03	1,849E+03	1,846E+03	1,844E+03
IY=12	1,921E+03	1,883E+03	1,853E+03	1,829E+03	1,810E+03	1,796E+03	1,786E+03	1,779E+03	1,774E+03	1,772E+03
IY=10	1,881E+03	1,835E+03	1,799E+03	1,770E+03	1,747E+03	1,730E+03	1,717E+03	1,708E+03	1,701E+03	1,697E+03
IY= 8	1,904E+03	1,840E+03	1,788E+03	1,746E+03	1,711E+03	1,683E+03	1,661E+03	1,643E+03	1,631E+03	1,621E+03
IY= 6	1,992E+03	1,914E+03	1,845E+03	1,786E+03	1,734E+03	1,690E+03	1,651E+03	1,619E+03	1,591E+03	1,569E+03
IY= 4	2,102E+03	2,016E+03	1,937E+03	1,866E+03	1,802E+03	1,744E+03	1,691E+03	1,644E+03	1,601E+03	1,563E+03
IY= 2	2,189E+03	2,099E+03	2,016E+03	1,939E+03	1,867E+03	1,801E+03	1,739E+03	1,683E+03	1,630E+03	1,582E+03
IZ=	21	22	23	24	25	26	27	28	29	30
IY=20	1,753E+03	1,755E+03	1,758E+03	1,759E+03	1,761E+03	1,761E+03	1,759E+03	1,752E+03	1,720E+03	1,573E+03
IY=18	1,837E+03	1,836E+03	1,835E+03	1,833E+03	1,829E+03	1,823E+03	1,815E+03	1,798E+03	1,748E+03	1,557E+03
IY=16	1,902E+03	1,902E+03	1,902E+03	1,901E+03	1,900E+03	1,898E+03	1,893E+03	1,879E+03	1,833E+03	1,643E+03
IY=14	1,844E+03	1,844E+03	1,844E+03	1,845E+03	1,845E+03	1,844E+03	1,841E+03	1,830E+03	1,788E+03	1,611E+03
IY=12	1,771E+03	1,772E+03	1,773E+03	1,774E+03	1,775E+03	1,775E+03	1,774E+03	1,765E+03	1,728E+03	1,568E+03
IY=10	1,695E+03	1,695E+03	1,696E+03	1,697E+03	1,699E+03	1,700E+03	1,701E+03	1,695E+03	1,665E+03	1,528E+03
IY= 8	1,615E+03	1,612E+03	1,611E+03	1,612E+03	1,614E+03	1,617E+03	1,619E+03	1,618E+03	1,597E+03	1,494E+03
IY= 6	1,550E+03	1,536E+03	1,526E+03	1,520E+03	1,518E+03	1,519E+03	1,523E+03	1,527E+03	1,522E+03	1,471E+03
IY= 4	1,530E+03	1,500E+03	1,475E+03	1,454E+03	1,438E+03	1,428E+03	1,423E+03	1,425E+03	1,437E+03	1,469E+03
IY= 2	1,537E+03	1,496E+03	1,460E+03	1,427E+03	1,399E+03	1,375E+03	1,358E+03	1,351E+03	1,371E+03	1,483E+03
IZ=	31	32	33	34	35	36	37	38	39	40
IY=20	1,674E+03									
IY=18	1,601E+03									
IY=16	1,647E+03									
IY=14	1,612E+03									
IY=12	1,569E+03									
IY=10	1,588E+03									
IY= 8	1,494E+03									
IY= 6	1,471E+03									
IY= 4	1,469E+03									
IY= 2	1,484E+03									
IZ=	41									

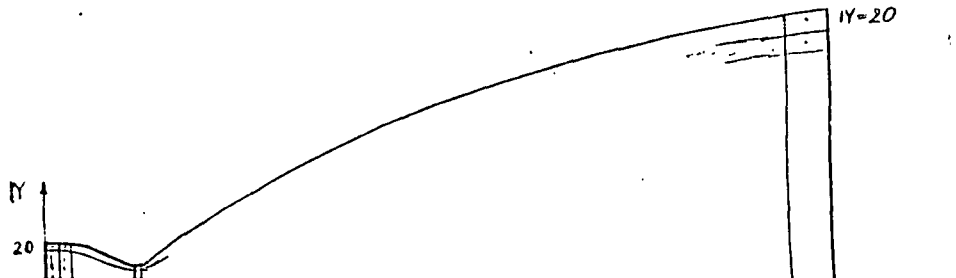

Table 8. Computer Printout for Absolute Pressure

throat

FIELD VALUES OF P1									
IY=20	2,022E+07	1,953E+07	1,938E+07	1,847E+07	1,636E+07	1,193E+07	8,832E+06	6,613E+06	4,239E+06	2,269E+06
IY=18	2,022E+07	1,950E+07	1,932E+07	1,840E+07	1,629E+07	1,249E+07	1,016E+07	7,822E+06	5,341E+06	2,965E+06
IY=16	2,021E+07	1,947E+07	1,924E+07	1,829E+07	1,624E+07	1,308E+07	1,094E+07	8,896E+06	6,607E+06	4,079E+06
IY=14	2,021E+07	1,941E+07	1,913E+07	1,817E+07	1,621E+07	1,352E+07	1,150E+07	9,673E+06	7,624E+06	5,202E+06
IY=12	2,021E+07	1,935E+07	1,902E+07	1,805E+07	1,621E+07	1,383E+07	1,192E+07	1,026E+07	8,421E+06	6,196E+06
IY=10	2,021E+07	1,928E+07	1,891E+07	1,795E+07	1,622E+07	1,406E+07	1,223E+07	1,070E+07	9,044E+06	7,034E+06
IY= 8	2,021E+07	1,921E+07	1,881E+07	1,787E+07	1,623E+07	1,421E+07	1,246E+07	1,104E+07	9,530E+06	7,720E+06
IY= 6	2,021E+07	1,914E+07	1,872E+07	1,780E+07	1,624E+07	1,432E+07	1,263E+07	1,129E+07	9,900E+06	8,259E+06
IY= 4	2,021E+07	1,909E+07	1,866E+07	1,776E+07	1,625E+07	1,440E+07	1,275E+07	1,147E+07	1,016E+07	8,650E+06
IY= 2	2,021E+07	1,906E+07	1,862E+07	1,773E+07	1,626E+07	1,444E+07	1,282E+07	1,158E+07	1,032E+07	8,883E+06
IZ=	1	2	3	4	5	6	7 NOZZLE	8	9	10
IY=20	1,638E+06	1,266E+06	9,945E+05	7,904E+05	6,360E+05	5,185E+05	4,298E+05	3,584E+05	3,027E+05	2,587E+05
IY=18	1,795E+06	1,302E+06	1,009E+06	7,979E+05	6,394E+05	5,191E+05	4,279E+05	3,560E+05	2,994E+05	2,547E+05
IY=16	2,361E+06	1,492E+06	1,072E+06	8,240E+05	6,522E+05	5,247E+05	4,282E+05	3,536E+05	2,951E+05	2,489E+05
IY=14	3,218E+06	1,971E+06	1,277E+06	9,060E+05	6,840E+05	5,357E+05	4,291E+05	3,492E+05	2,879E+05	2,401E+05
IY=12	4,162E+06	2,673E+06	1,711E+06	1,131E+06	7,927E+05	5,838E+05	4,463E+05	3,507E+05	2,814E+05	2,297E+05
IY=10	5,071E+06	3,471E+06	2,312E+06	1,528E+06	1,030E+06	7,178E+05	5,174E+05	3,845E+05	2,935E+05	2,293E+05
IY= 8	5,881E+06	4,262E+06	2,980E+06	2,041E+06	1,386E+06	9,490E+05	6,617E+05	4,714E+05	3,435E+05	2,557E+05
IY= 6	6,551E+06	4,962E+06	3,617E+06	2,566E+06	1,788E+06	1,236E+06	8,582E+05	6,016E+05	4,276E+05	3,087E+05
IY= 4	7,050E+06	5,502E+06	4,130E+06	3,008E+06	2,147E+06	1,511E+06	1,057E+06	7,406E+05	5,222E+05	3,717E+05
IY= 2	7,348E+06	5,821E+06	4,438E+06	3,281E+06	2,375E+06	1,693E+06	1,196E+06	8,418E+05	5,931E+05	4,198E+05
IZ=	11	12	13	14	15	16	17	18	19	20
IY=20	2,236E+05	1,953E+05	1,723E+05	1,535E+05	1,379E+05	1,249E+05	1,137E+05	1,043E+05	9,613E+04	8,902E+04
IY=18	2,191E+05	1,905E+05	1,673E+05	1,484E+05	1,328E+05	1,198E+05	1,088E+05	9,946E+04	9,146E+04	8,453E+04
IY=16	2,122E+05	1,829E+05	1,593E+05	1,401E+05	1,243E+05	1,113E+05	1,004E+05	9,128E+04	8,349E+04	7,683E+04
IY=14	2,024E+05	1,725E+05	1,485E+05	1,291E+05	1,133E+05	1,004E+05	8,978E+04	8,091E+04	7,347E+04	6,719E+04
IY=12	1,902E+05	1,594E+05	1,352E+05	1,159E+05	1,004E+05	8,786E+04	7,760E+04	6,917E+04	6,220E+04	5,641E+04
IY=10	1,828E+05	1,484E+05	1,224E+05	1,024E+05	8,683E+04	7,455E+04	6,476E+04	5,688E+04	5,049E+04	4,528E+04
IY= 8	1,943E+05	1,506E+05	1,188E+05	9,535E+04	7,779E+04	6,446E+04	5,421E+04	4,626E+04	4,003E+04	3,513E+04
IY= 6	2,266E+05	1,690E+05	1,282E+05	9,878E+04	7,731E+04	6,143E+04	4,955E+04	4,058E+04	3,374E+04	2,848E+04
IY= 4	2,677E+05	1,952E+05	1,443E+05	1,081E+05	8,216E+04	6,329E+04	4,943E+04	3,914E+04	3,145E+04	2,560E+04
IY= 2	2,995E+05	2,157E+05	1,570E+05	1,158E+05	8,641E+04	6,535E+04	5,009E+04	3,890E+04	3,062E+04	2,443E+04
IZ=	21	22	23	24	25	26	27	28	29	30
IY=20	8,272E+04	7,718E+04	7,223E+04	6,776E+04	6,375E+04	6,011E+04	5,688E+04	5,324E+04	4,883E+04	3,985E+04
IY=18	7,846E+04	7,312E+04	6,839E+04	6,416E+04	6,036E+04	5,693E+04	5,375E+04	5,055E+04	4,648E+04	3,811E+04
IY=16	7,108E+04	6,607E+04	6,169E+04	5,782E+04	5,439E+04	5,131E+04	4,850E+04	4,572E+04	4,219E+04	3,491E+04
IY=14	6,185E+04	5,788E+04	5,334E+04	4,993E+04	4,696E+04	4,434E+04	4,199E+04	3,970E+04	3,682E+04	3,083E+04
IY=12	5,157E+04	4,751E+04	4,408E+04	4,118E+04	3,872E+04	3,660E+04	3,476E+04	3,301E+04	3,084E+04	2,625E+04
IY=10	4,102E+04	3,752E+04	3,464E+04	3,227E+04	3,031E+04	2,870E+04	2,736E+04	2,616E+04	2,470E+04	2,151E+04
IY= 8	3,125E+04	2,817E+04	2,574E+04	2,382E+04	2,232E+04	2,116E+04	2,028E+04	1,958E+04	1,877E+04	1,693E+04
IY= 6	2,442E+04	2,129E+04	1,888E+04	1,704E+04	1,567E+04	1,468E+04	1,402E+04	1,362E+04	1,336E+04	1,274E+04
IY= 4	2,115E+04	1,775E+04	1,514E+04	1,313E+04	1,162E+04	1,050E+04	9,715E+03	9,239E+03	9,066E+03	9,261E+03
IY= 2	1,976E+04	1,621E+04	1,350E+04	1,141E+04	9,809E+03	8,592E+03	7,692E+03	7,083E+03	6,821E+03	7,262E+03
IZ=	31	32	33	34	35	36	37	38	39	40
IY=20	1,137E+04									
IY=18	1,119E+04									
IY=16	1,111E+04									
IY=14	1,099E+04									
IY=12	1,084E+04									
IY=10	1,067E+04									
IY= 8	1,049E+04									
IY= 6	1,032E+04									
IY= 4	1,015E+04									
IY= 2	1,003E+04									
IZ=	41									

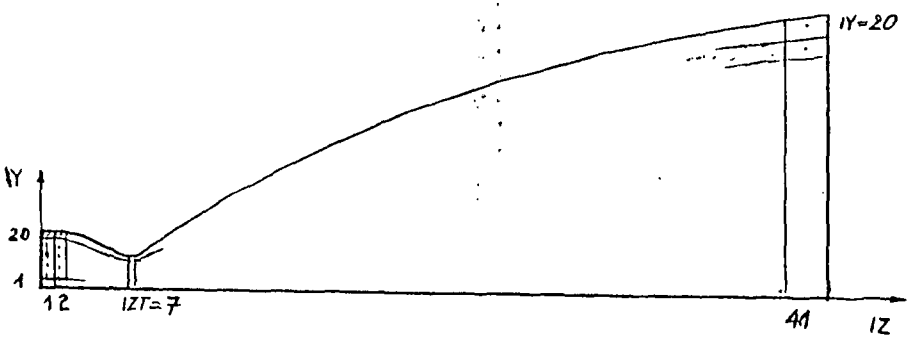

Table 9. Computer Printout for Mach Number

throat

FIELD VALUES OF MACH

IY=20	1.201E-01	1.489E-01	1.858E-01	2.930E-01	5.160E-01	7.710E-01	9.678E-01	1.092E+00	1.137E+00	1.069E+00
IY=18	1.731E-01	1.883E-01	2.752E-01	4.329E-01	6.517E-01	8.302E-01	9.995E-01	1.171E+00	1.334E+00	1.470E+00
IY=16	1.768E-01	1.961E-01	2.836E-01	4.340E-01	6.222E-01	7.878E-01	9.426E-01	1.102E+00	1.272E+00	1.433E+00
IY=14	1.821E-01	2.055E-01	2.926E-01	4.335E-01	6.018E-01	7.590E-01	9.022E-01	1.046E+00	1.210E+00	1.382E+00
IY=12	1.888E-01	2.157E-01	3.016E-01	4.331E-01	5.875E-01	7.375E-01	8.716E-01	1.003E+00	1.157E+00	1.333E+00
IY=10	1.959E-01	2.255E-01	3.097E-01	4.330E-01	5.775E-01	7.213E-01	8.478E-01	9.683E-01	1.112E+00	1.285E+00
IY= 8	2.029E-01	2.343E-01	3.167E-01	4.334E-01	5.705E-01	7.090E-01	8.294E-01	9.413E-01	1.074E+00	1.239E+00
IY= 6	2.091E-01	2.415E-01	3.224E-01	4.339E-01	5.657E-01	6.998E-01	8.154E-01	9.206E-01	1.044E+00	1.198E+00
IY= 4	2.140E-01	2.468E-01	3.264E-01	4.343E-01	5.625E-01	6.935E-01	8.054E-01	9.057E-01	1.022E+00	1.166E+00
IY= 2	2.170E-01	2.499E-01	3.288E-01	4.347E-01	5.608E-01	6.897E-01	7.995E-01	8.968E-01	1.008E+00	1.146E+00
IZ=	1	2	3	4	5	6	7	8	9	10
IY=20	1.001E+00	1.075E+00	1.204E+00	1.326E+00	1.438E+00	1.541E+00	1.600E+00	1.658E+00	1.721E+00	1.786E+00
IY=18	1.569E+00	1.690E+00	1.824E+00	1.955E+00	2.077E+00	2.188E+00	2.289E+00	2.382E+00	2.465E+00	2.539E+00
IY=16	1.574E+00	1.720E+00	1.863E+00	2.001E+00	2.133E+00	2.256E+00	2.367E+00	2.469E+00	2.563E+00	2.647E+00
IY=14	1.544E+00	1.710E+00	1.881E+00	2.039E+00	2.187E+00	2.323E+00	2.447E+00	2.559E+00	2.660E+00	2.751E+00
IY=12	1.508E+00	1.679E+00	1.860E+00	2.043E+00	2.214E+00	2.372E+00	2.515E+00	2.641E+00	2.754E+00	2.854E+00
IY=10	1.466E+00	1.641E+00	1.819E+00	2.005E+00	2.188E+00	2.363E+00	2.525E+00	2.673E+00	2.805E+00	2.922E+00
IY= 8	1.420E+00	1.597E+00	1.772E+00	1.949E+00	2.129E+00	2.304E+00	2.472E+00	2.631E+00	2.777E+00	2.912E+00
IY= 6	1.373E+00	1.549E+00	1.722E+00	1.893E+00	2.063E+00	2.231E+00	2.393E+00	2.549E+00	2.697E+00	2.838E+00
IY= 4	1.332E+00	1.504E+00	1.675E+00	1.842E+00	2.005E+00	2.164E+00	2.319E+00	2.468E+00	2.612E+00	2.751E+00
IY= 2	1.309E+00	1.473E+00	1.641E+00	1.805E+00	1.964E+00	2.118E+00	2.267E+00	2.412E+00	2.552E+00	2.688E+00
IZ=	11	12	13	14	15	16	17	18	19	20
IY=20	1.890E+00	1.911E+00	1.969E+00	2.023E+00	2.073E+00	2.119E+00	2.159E+00	2.193E+00	2.223E+00	2.248E+00
IY=18	2.605E+00	2.663E+00	2.714E+00	2.759E+00	2.798E+00	2.832E+00	2.862E+00	2.889E+00	2.912E+00	2.934E+00
IY=16	2.722E+00	2.788E+00	2.847E+00	2.898E+00	2.942E+00	2.981E+00	3.015E+00	3.045E+00	3.071E+00	3.095E+00
IY=14	2.832E+00	2.904E+00	2.968E+00	3.023E+00	3.071E+00	3.113E+00	3.149E+00	3.180E+00	3.207E+00	3.231E+00
IY=12	2.942E+00	3.019E+00	3.087E+00	3.147E+00	3.198E+00	3.243E+00	3.282E+00	3.315E+00	3.343E+00	3.367E+00
IY=10	3.025E+00	3.115E+00	3.193E+00	3.261E+00	3.319E+00	3.370E+00	3.413E+00	3.450E+00	3.482E+00	3.508E+00
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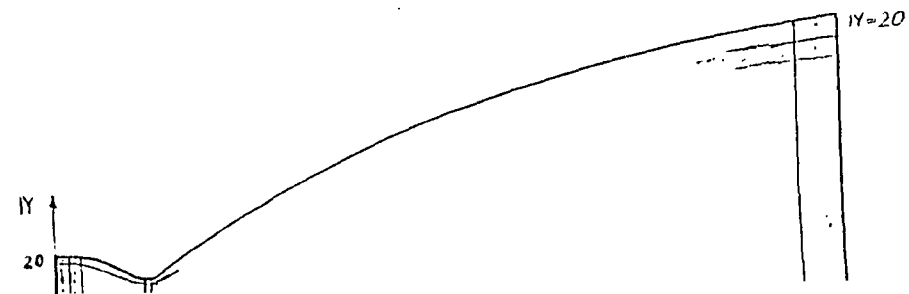
IY= 4	2.883E+00	3.009E+00	3.130E+00	3.244E+00	3.352E+00	3.455E+00	3.552E+00	3.643E+00	3.728E+00	3.808E+00
IY= 2	2.819E+00	2.945E+00	3.067E+00	3.185E+00	3.299E+00	3.408E+00	3.514E+00	3.615E+00	3.713E+00	3.806E+00
IZ=	21	22	23	24	25	26	27	28	29	30
IY=20	2.269E+00	2.286E+00	2.300E+00	2.310E+00	2.318E+00	2.324E+00	2.331E+00	2.343E+00	2.380E+00	2.565E+00
IY=18	2.953E+00	2.970E+00	2.987E+00	3.002E+00	3.016E+00	3.030E+00	3.044E+00	3.066E+00	3.130E+00	3.400E+00
IY=16	3.116E+00	3.135E+00	3.153E+00	3.170E+00	3.186E+00	3.203E+00	3.221E+00	3.249E+00	3.318E+00	3.592E+00
IY=14	3.251E+00	3.270E+00	3.286E+00	3.302E+00	3.317E+00	3.331E+00	3.348E+00	3.373E+00	3.438E+00	3.703E+00
IY=12	3.388E+00	3.406E+00	3.422E+00	3.436E+00	3.449E+00	3.462E+00	3.476E+00	3.498E+00	3.558E+00	3.806E+00
IY=10	3.531E+00	3.550E+00	3.565E+00	3.579E+00	3.590E+00	3.600E+00	3.611E+00	3.629E+00	3.682E+00	3.902E+00
IY= 8	3.684E+00	3.707E+00	3.726E+00	3.740E+00	3.751E+00	3.758E+00	3.765E+00	3.775E+00	3.814E+00	3.985E+00
IY= 6	3.818E+00	3.859E+00	3.893E+00	3.919E+00	3.937E+00	3.948E+00	3.952E+00	3.954E+00	3.967E+00	4.050E+00
IY= 4	3.881E+00	3.948E+00	4.007E+00	4.059E+00	4.101E+00	4.133E+00	4.154E+00	4.159E+00	4.142E+00	4.074E+00
IY= 2	3.894E+00	3.978E+00	4.057E+00	4.129E+00	4.195E+00	4.251E+00	4.296E+00	4.319E+00	4.286E+00	4.068E+00
IZ=	31	32	33	34	35	36	37	38	39	40
IY=20	2.410E+00									
IY=18	3.266E+00									
IY=16	3.501E+00									
IY=14	3.620E+00									
IY=12	3.731E+00									
IY=10	3.836E+00									
IY= 8	3.933E+00									
IY= 6	4.020E+00									
IY= 4	4.079E+00									
IY= 2	4.104E+00									
IZ=	41									



the following meaning:

ZG - dimensional axial distance (forward cell face) [m]
ZND - nondimensional axial distance $(Z - Z_T)/r_T$[-]
YN - local non-dimensional radius of the nozzle r/r_T [-]
ANG - wall inclination angle [rad]
PW - pressure near solid wall [N/m^2]
PAX - pressure near the axis [N/m^2]
TW - wall temperature [^oK]
TNY - near wall temperature [^oK]
TAX - temperature at the axis [^oK]

Table 2 provides similar information in British Units p [psia], T [R^o], where the heading (ZG:TH) = Z/r_T represents nondimensional axial distance and YN - is the nozzle radius in meters.

The wall and axis pressure distributions in the logarithmic scale (log P) are provided in Table 3.

A summary of the wall heat transfer results is printed in Table 4 where AREA (m^2) is the wall area in contact with the control volume, HTCOEF is the heat coefficient (W/m^2K), TW-T(NY) represents the temperature difference in ^oK between the wall and the "near wall grid node", QFLX (W/m^2) is the heat flux, QDOT (W) is the local cell heat flow rate and QSUM (1-IZ) is the wall heat flow rate integrated along the wall from the injector face up to the IZ-th axial plane.

Tables 5 to 9 are reproductions of the computer printout for the flow field variables including:

Table 5, WCRT - cartesian component of axial velocity [m/s];
Table 6, VCRT - cartesian component of radial velocity [m/s];
Table 7, TEMP - absolute temperature [^oK];
Table 8, P1 - absolute static pressure [N/m^2]; and
Table 9, MACH - Mach number [-].

Calculated global performance parameters for the thrust chamber are:

- throat mass flow rate
  $\dot{m}_T$ = 456.72 kg/s = 1007 lb/s;
- mass flow rate at the exit from the nozzle
  $\dot{m}_{ex}$ = 456.50 kg/s;

- cross-sectional mass imbalance between the throat and exit
  m_e = (456.72 - 456.5)/456.72 = 0.048%;
- thrust calculated as:
  $T = \Sigma P_{NY} \cdot A_{WALL} \cdot \sin(\alpha_{wall}) = 19.353 \cdot 10^5$ N ≅ 435,000 lbF
  summation is taken over thrust chamber wall and injector face.

Figure 5.10 illustrates axial components of the pressure forces acting on the inner walls of the thrust chamber and used for calculating the thrust.

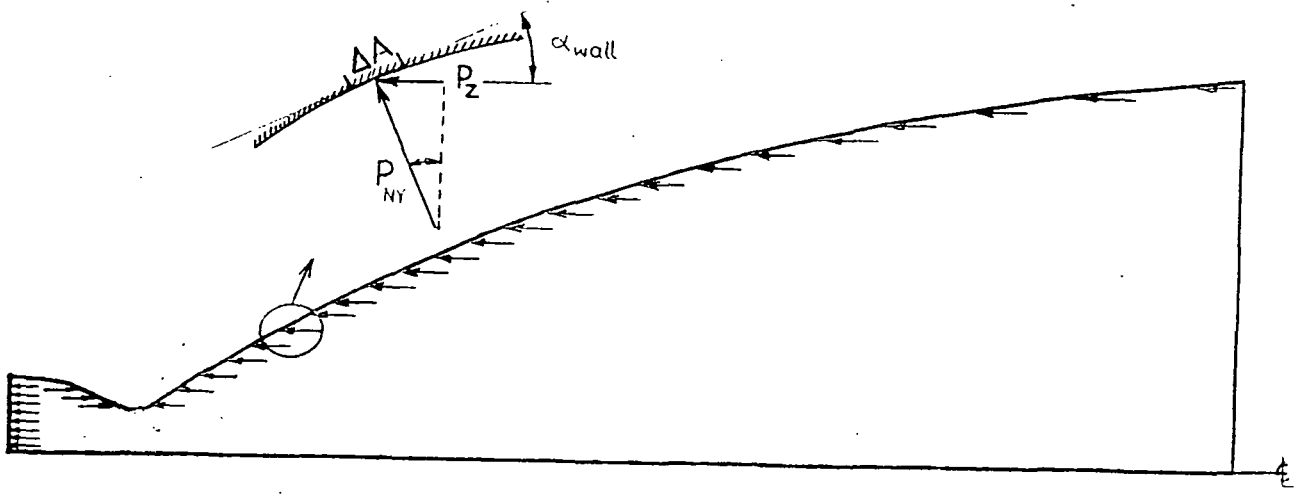


Figure 5.10 Pressure Forces Acting on Rocket Chamber and Nozzle Walls

Force acting on injector face was calculated based on the first node pressures rather than on the supplied data of inlet pressure. With the inlet pressure supplied the thrust is T - 440,000.

- specific impulse:

$$I_{SP} = \frac{435,000.}{1007} = 432.0 \text{ sec}$$

5.2 Discussion of the Computational Results

The results obtained reveal all expected features of the nozzle flows. The velocity vector field presented in Figure 5.1 and 5.2 indicate flow acceleration in the expansion part of the nozzle. The viscous effects are visible from velocity profiles presented in Figure 5.3. As expected the velocity profile in the throat region has a maximum near the wall. While in further downstream cross-sections the maximum velocity location is shifted toward the axis. The viscous effects in the flow are visible in the downstream planes reflected in the variation of the velocity profile extending up to the nozzle axis.

The Mach number contours are shown in Figures 5.4 and 5.5 The sonic line ($M_a = 1$) emanates from the geometrical throat wall point and reaches the nozzle axis at a further downstream location in a parabolic profile fashion. The shape and location of $M_a = 1$ line is typical for the transonic nozzle flow field.

Inspection of Ma = const contours downstream of throat region indicate the existence of a shock generated at the position of the second wall curvature tangency point (location where the radius of curvature meets nozzle bell shape). In this region Mach-isolines exhibit a change of curvature in the vicinity of the wall. The "barrel type" shock wave is well visible in the region of fine grid just downstream of throat and extends almost up to the exit.

The shape of the barrel shock is clearly resolved in the upstream part of the nozzle. The downstream resolution of the shock is affected by the grid coarseness and by approximations in the exit boundary conditions specifications.

Examination of temperature and pressure contours reveals that the largest pressure gradients exist within the throat and steepest temperature gradients downstream of the throat near the wall curvature tangency point. Note that temperature contour levels are presented with uniform intervals.

In all contour-plot figures, the geometry outline extends up to slab 41, which is located downstream of the nozzle exit. The dotted line indicates the location of the exit. There are, however, indications of the influence of the uniform

exit pressure assumption on the inner flow field profiles. Contours of Ma, T and p indicate some "perturbations" near the nozzle exit. Therefore the results in the near-exit region should be interpreted with caution.

Possible improvements in the specification of exit boundary conditions are discussed in Section 6.

Interesting observations can also be drawn from Figures 5.8 and 5.9 presenting axial distributions of temperatures and pressures. The axial temperature profile T_{axis} is typical for inviscid nozzle flows. The near wall temperature T_{NY} (in Figure 5.8) illustrates a complex phenomenon of expansion portraying the kinetic heating and convective heat transfer between the combustion gases and cooled nozzle wall.

Distribution of the pressure profiles P_{axis} and P_{wall} shows that just after the downstream "tangency point" pressure near the wall becomes larger than that at the axis. Close to the exit the difference between the wall and axis pressure becomes:

$$P_{wall} - P_{axis} \cong 39800 - 6900 = 32900 \text{ N/m}^2 \cong 4.77 \text{ psi}$$

This confirms our earlier conclusion, that for accurate calculation of "near exit" flow details, a better exit boundary condition is required.

Finally, the analysis of the global parameters, such as total mass flow rates, thrust and specific impulse is summarized below.

- Cross-sectional mass flow rates are perfectly preserved throughout the chamber.
- Calculated temperatures within the combustion chamber and the nozzle are overpredicted due to the "one-step" reaction model assumption used in present calculations.
- Finer grid in the regions, where significant axial pressure gradient exists is necessary for more accurate results. Predicted key parameters such as thrust and specific impulse

require an accurate pressure distribution in the contraction as well as in the expansion parts of the nozzle*.

- Further studies of the "boundary layer and main stream" interaction procedure is required with attention on "near wall" shear stresses and heat flux calculations. It is envisioned that direct and accurate calculation of the boundary layer structure is well within model capabilities and can help in understanding several phenomena of shock-boundary layer interaction.

- Application of a chemical "equilibrium model" and the complex kinetic effects are suggested for the further studies. The incorporation of finite rate chemistry would be especially interesting to study near wall reaction processes and interaction between chemistry and heat transfer.

* Results of an additional run (results of which are not presented here) with four extra grid slabs in the contraction part of the nozzle revealed that the calculated specific impulse I_{sp} increased from 432.0 sec for 41 x 20 grid to 437.9 sec for 45 x 20 grid.

Section 6
CFD MODEL ASSESSMENT

The salient features and general advantages of the proposed CFD approach and computer code (PHOENICS) have already been described in Section 2. This section discusses the assessment considerations listed in the project objectives (Section 1.2, page 1-5). Each question is answered in specific reference to PHOENICS's performance for the problem considered.

6.1 Time Requirement for Input Data Preparation

Section 4 has provided the details of the input data preparations. The time requirement for input data preparation can vary depending upon the complexity of the test case and on the experience of the engineer. For experienced engineer modification of the existing SATELLITE and SUBROUTINE GROUND for the SSME thrust chamber test case may take:

- only few minutes for grid or boundary condition change or for additional printout arrangement, to
- few days to include new combustion model, new wall functions or other model improvements.

To facilitate new users, CHAM conducts three-day training courses with hand-on workshop sessions. These courses are held once in every three months at CHAM. Specific courses are also held at client's site on request.

6.2 Computer Requirement

PHOENICS is a portable code. At present the code is operational at various main frames e.g. CRAY-1, CYBER 205, CDC-7600, IBM, UNIVAC, and 32-bit mini computers such as: VAX, PRIME, Perkin Elmer and Apollo.

The code uses ANSI Standard FORTRAN and is not optimized or vectorized for any particular computer. For complex problems i.e. those with large number of control cells (e.g. $\geq$ 20,000), out-of-core storage is usually necessary on mini computers. Due to extra I/O operations of the out-of-core storage use, this usually slows down the execution (up to 50%). The present work was done on a Perkin-Elmer, with 820 control cells and full in-core storage.

6.3 Execution Time Requirements

The current problems required 400 sweeps (iterations) for the convergence of the iterative solution procedure. The convergence was judged by checking the mass residuals as well as the calculated flow variables. The sum of absolute values of residuals at all cells was reduced four orders of magnitude in 400 sweeps.

The sweep to sweep variation of flow variables were within 0.1% of their final values.

Execution time of the base case was 90 ÷ 110 minutes of P-E, 3205. Generally main frame computers are about 20 times faster.

6.4 Accuracy of the Results

Accuracy of the results can be best determined by direct comparisons with the measurements. In the absence of measured data, the following considerations may be useful.

1. There are no mass, energy or momentum imbalances in the calculations . This is due to the conservative formulation of the numerical scheme.

2. Results can be somewhat sensitive to the grid resolution. Generally, grid-sensitivity studies should be performed for each new problem This has been recommended for SSME Chamber problem, too.

3. Results may also be sensitive to the physical models employed. Each of the physical models viz: for turbulence, combustion, wall shear stresses, and heat transfer have been described in detail. This should facilitate a fair assessment. Alternative models can be employed and assessed.

6.5 Status of the Code

The PHOENICS code is in use at more that 100 research organizations over the world. Due to the extensive usage, the code is fairly well debugged. However, modifications for further improvements in the solution scheme as well as in the

user orientation of the code are in continuous progress. These are consolidated and released to the users periodically (i.e. once in a year or two) by providing the upgraded code.

The code has provisions for body fitted coordinates, which are essential for accuracy of nozzle flow calculations. Non-orthogonal grids can be generated fairly easily with the build-in "transfinite mapping" routine or can be read-in from user supplied grid preparation preprocessor code.

The code has provisions for inclusion of new physical models by the user. This makes the code suitable for both routine engineering analyses as well as for research purposes.

Section 7
CONCLUSIONS AND RECOMMENDATIONS

Reported calculations have demonstrated that the basic capability exists of simulating reactive multidimensional flow in rocket engines for subsonic, transonic and supersonic compressible conditions by solving the Navier-Stokes equations for the entire nozzle geometry. Results of a single test case, presented in this present report, indicate good accuracy of the calculated data. All physical aspects of transonic flow with heat transfer in the nozzle have been predicted. Several improvements should be made in the mathematical model to make it a valuable tool for optimizing design and performance analysis of rocket engines.

The proposed modifications are especially oriented to improve mathematical models of physical processes. With suggested improvements and after verification through comparison with test results, sensitivity studies can be conducted leading to optimum rocket motor projections.

Some of the improvements are discussed below.

7.1 Improvements in Combustion Modeling

The currently employed one-step reaction in the present study has been used mainly for convenience. Mimimum coding was required to calculate stable species concentrations (O_2, H_2 and H_2O). It is recommended that one of the following two techniques should be used for further improvement:

a) chemical equilibrium model; or

b) chemical kinetics of chain reactions.

The first approach is the simpler one and requires no additional differential transport equation to be solved for. Local composition (O_2, H_2, O, H, OH, H_2, H_2O, HO_2 etc. . .) can be obtained by solving a system of algebraic equations. General subroutines for the Gauss function minimization are readily available (Reference 13) and can be incorporated into the calculation scheme. For the H_2 - O_2 reaction mechanism a simple and fast procedure can be used without employing the Gauss function minimization. The task can be reduced to solving two

nonlinear algebraic equations for m_H and m_O. The remaining species composition can be obtained either from the stoichiometric relation or from equilibrium constants. Appendix D provides detailed derivation of the above equations and outlines the appropriate solution procedure.

The chemical kinetics calculations are recommended as a second step of the combustion simulation. The reaction mechanism between H_2 and O_2 is well established and rate constants are known. CHAM has extensive experience in using chemical kinetics modeling for the rocket plumes (References 19 and 20). Relevant subroutines are readily available and only require careful incorporation into the PHOENICS' GROUND station and initial tests.

7.2 Improvements in Wall Boundary Layer Treatment

The "wall functions", applied in the present method, are based on experimental data for parallel flows in simple shear layers. The wall functions which account for the axial pressure gradient have not, to our knowledge, been extensively tested and require more attention during recommended verification studies. An alternative approach, also recommended for future investigations, has been recently presented by Launder (Reference 16) in which wall functions are replaced by local near-wall solution of the bounary layer equation. A separate grid structure is used between the near wall node and the solid wall. The resultant solution (for the velocity and for temperature) is integrated providing the wall shear stresses (or heat flux) for the "basic grid" (macroscopic) calculations. A locally parabolic solution layer (PSL) is used to calculate boundary conditions for "macroscopic" equations. The proposed approach would combine the efficiency of implicit iterative schemes with the accuracy of fine grid time marching methods for shock-boundary layer calculations (see NASA Ames work in Reference 35 and 36). Figure 7.1 (Reference 16) schematically presents all three near wall treatments.

a) currently used in PHOENICS "wall function" approach;

b) fine grid solution of fully elliptic equations; and

c) Elliptic - Parabolic Solution Layer (PSL) approach.

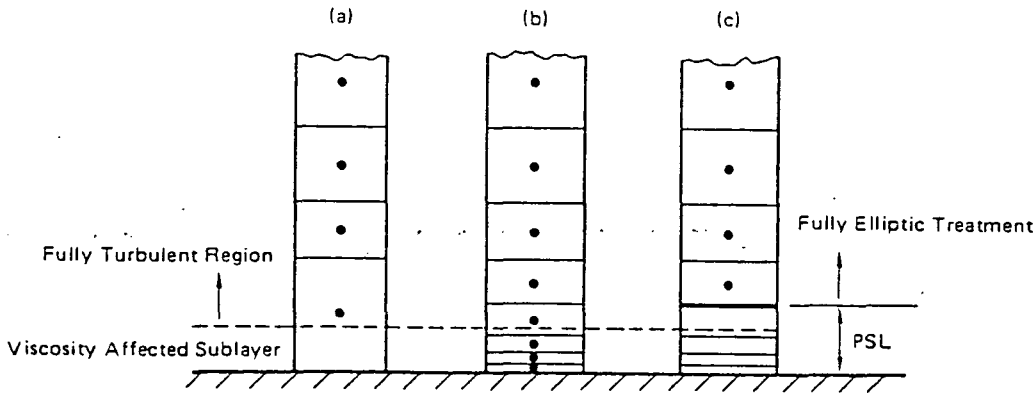


Figure 7.1 Illustration of Wall Boundary Layer Treatments

7.3 Incorporation of the Thrust Chamber Cooling System into the Computational Domain

In the present computational studies the computational domain extended up to the inner wall of the thrust chamber. The thermal boundary condition was provided in the form of specified wall temperatures T_{wall}. For the design or optimization studies, or even for transient analysis a priori specification of T_{wall} is uncertain and inaccurate. The coolant temperature at the inlet to the cooling jacket can be specified more accurately. The coolant flow and its thermal coupling with the thrust chamber gases should be embodied into a general model with the computational grid extended up to the cooling jacket.

In future studies the coolant fluid flow and heat transfer as well as heat conduction within the thrust chamber walls should be included into the model. The necessary modification would require specification of -

- solid wall geometry (wall thickness, and shape) and thermal properties (thermal conduction and heat capacity);
- cooling system geometry (inlet locations, jacket cross-section area, flow direction, etc), and;
- coolant properties.

CHAM has the necessary experience in simulating the conjugate heat transfer problems (References 33 and 34).

7.4 Simulation with Two-Phase Flow Approaches

Detailed information on the flame structure and combustion efficiency in liquid propelled rocket engines requires a two-phase flow and combustion formulation. The two-phases being considered are:

- Liquid phase of cryogenic H_2 or O_2 streams, and
- Vapor (gaseous) mixture of unburned reactants and combustion gases.

There are two basic approaches to model the two-phase flow with combustion:

- Eulerian approach in which the gas and solid phases are treated as interpenetrating continuum, described by the conservation equations in the Eulerian frame, and
- Eulerian-Lagrangean (E-L) approach in which the liquid phase is described in a lagrangean formulation (coordinate system moving with the droplet) and the gas phase in Eulerian coordinates.

The first technique has been developed by Spalding (20), Williams (21) and Westbrook (22) who modeled the spray through conservation equations utilizing a statistical distribution function in Eulerian frame. Similar approach has been employed by Swithenbank (23) for modeling a 3-dimensional gas turbine combustor. In all these applications a velocity slip between the gas and drops or particles has been neglected. An Eulerian approach for two-phase flows with velocity slip has been developed by Spalding (24) and used by Malin et al (25) in two-phase coal combustion and by authors (26) of this document for spray combustion in diesel engines.

The second (E-L) approach, introduced by Crowe (References 27 and 28) has been employed for several two-phase coupled fluid flows and combustion calculations (References 29, 30, 31 and 32). It has also been used for predicting the injection of fluid flow with combustion of rocket engines using liquid propellants (Reference 3).

The PHOENICS computer code has a built in option for the first approach (fully Eulerian) which can be easily used for the SSME combustion calculations. Specifications of appropriate boundary conditions and the evaporation rate formula are required. CHAM's past experience in diesel engine simulation (References 8 and 26) can be utilized effectively.

7.5 Improvements in the Grid Generation Procedure

It is well known that the geometrical details of the nozzle have significant influence on the flow pattern in rocket engines. A Body Fitted Coordinate (BFC) system must be used for nozzle numerical studies. It is also known, however, that the grid selection can influence both the numerical convergence rate as well as the accuracy of the predicted results. Selection of the grid distribution for the entire calculation domain, in which the Navier-Stokes equations are solved, requires special attention.

The currently employed nonorthogonal grid is generated by a simple method called "shearing transformation" in which radial lines (z = const) coincide with cartesian y = const lines while axial lines are calculated at each z = const slab from nondimensional radial distance.

An alternative practice would be to use an orthogonal grid, generated within the combustion chamber and nozzle. For this, however, a preprocessor grid generation package is required which would automatically generate the grid distribution.

It is recommended that for the future studies of the nozzle flows a Grid Generation Package (GGP) should be developed to:

a) quickly generate a grid in any two-dimensional domain;
b) interact in any Navier-Stokes equation solution computer code;
c) provide results in both computer interactive-session as well as "batch-job" mode;
d) generate any coordinate system including orthogonal, nonorthogonal with easy specification of grid attraction in desired regions (walls, throat, shock waves, flame fronts, etc.); and
e) be coupled with the N-S equation solver code in the "grid adaptive" mode.

CHAM has the necessary experience and personnel to quickly assemble, and deliver such a GPP code. Several phases of the BFC preprocessing have been already developed and are available as the GGP segments.

7.6 Recommendations for Further Studies and Code Use by NASA MSFC Personnel

PHOENICS courses and workshops, which are regularly organized at CHAM NA, will provide a good introduction to successful code utilization. In addition, it is recommended that the listing of SATELLITE and GROUND should be studied by the user. Most of the simple changes can be done by modifying SATELLITE.

Familiarity with the code is best gained by performing calculations with different flow conditions. The next step can be to change the grid distribution in axial and radial directions. The following steps could involve calculation of fluid properties such as molecular viscosity as a function of temperature (modifications in GROUND ch. 11), calculation of laminar and turbulent Prandtl numbers, etc.

Another action could involve the introduction of chemical equilibrium. A separate subroutine could be attached to GROUND and called from Chapter 10 before the density is calculated. Appendix D provides a complete set of algebraic equations which can be solved by a Newton Method.

For more complex modifications, consultation with CHAM is recommended to minimize the effort and hence cost and time.

Section 8

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APPENDIX A

CALCULATION OF THE INLET CONDITIONS FOR SSME NOZZLE TEST CASE

APPENDIX A
CALCULATION OF INLET COMPOSITION

For this study it is assumed that the fuel and oxygen are injected to the SSME combustion chamber in the liquid form. A single phase, homogeneous mixing assumption requires recalculation of the data provided for the liquid composition at temperatures below the boiling point T_B to the equivalent composition at selected temperatures T_{in} above T_B. For the present study $T_{in} = 300^oK$ has been selected (one of the reasons is available $C_p \sim T$ dependence valid for 300 - 5000^oK temperature range).

In reality SSME preburner combustion products are reacted with additional oxygen in a second combustion process in the main chamber. The assumption is made that the resulting reaction products are the same if oxygen and hydrogen are reacted in an equilibrium fashion with appropriate enthalpy values.

The input data are:

- Enthalpies

$$\tilde{h}_{H_2} = -1837.660 \frac{cal}{mol} = -3.84695 \cdot 10^6 \text{ J/kg}$$

$$\tilde{h}_{O_2} = -2884.385 \frac{cal}{mol} = -3.77386 \cdot 10^6 \text{ J/kg}$$

- Composition at the injection plane

$$f = \frac{m^o_{O_2}}{m^o_{H_2}} = 6.054851 \qquad m^o_{H_2} = \frac{1}{1+f} = 0.141746$$

$$m^o_{H_2} + m^o_{O_2} + m^o_{H_2O} = 1 \qquad m^o_{O_2} = \frac{1}{1+f} = 0.858254$$

$$m^o_{H_2O} = 0$$

Mixture enthalpy

$$\tilde{h}^o_m = m^o_{H_2} \tilde{h}_{H_2} + m^o_{O_2} \tilde{h}_{O_2} = -5.7768 \cdot 10^5 \text{ J/kg}$$

Assuming an "adiabatic" process i.e. $\tilde{h}^{o}_{m} = \tilde{h}_{m}$ and $T = 300^{o}K$ the mixture composition can be calculated by a simple iterative procedure. By converting part of $m^{o}_{O_2}$ and $m^{o}_{H_2}$ into m_{H_2O} at constant $\tilde{h}_{m}$ the temperature of the mixture is rising. During the iteration process the m_{H_2O} concentration was incremented to the level at which the mixture temperature reached $T = 300^{o}K$. Calculated, in this way the inlet composition is:

$$m_{H_2O} = 0.0434175$$

$$m_{H_2} = \frac{1 - m_{H_2O}}{1 + f} = .135592$$

$$m_{O_2} = m_{H_2} \cdot f = .82099$$

APPENDIX B

WALL FUNCTIONS FOR FLOWS WITH SIGNIFICANT PRESSURE GRADIENTS

Appendix B

WALL FUNCTIONS FOR FLOWS WITH SIGNIFICANT PRESSURE GRADIENTS

Calculation of the transonic flow in the nozzles requires careful calculation of the wall boundary layer and main stream interaction. In the JANNAF standard procedure a few iterative computations between TDK - inviscid hydrodynamics and BLIMP - boundary layer flow codes are necessary to establish the correct boundary layer displacement thickness while matching imposed conditions at the potential wall.

The simultaneous solution of the Navier Stokes equations for the entire flow domain implicity accounts for the coupling between the viscous boundary layer and the core flow. An accurate resolution of the boundary layer, however, is as important as in the JANNAF procedure.

In the BLIMP program several grid nodes can be used across the boundary layer for accurate calculation of the shear stresses and heat fluxes. In the direct solution of the N-S equations the grid nodes have to be redistributed in the entire cross-section of the nozzle. To ensure ecomony and good accuracy in the direct neighborhood of the solid boundary a "wall function" concept is used.

The wall functions permit to calculate the shear stresses and heat flux at the "near wall" grid node and the solid wall. A semi-analytical solution of the simplified N-S equations are used to devise the wall functions as discussed below:

Implications of the Van Driest Formula

The most commonly known Prandtl mixing length formula expresses the shear stresses τ in terms of the mixing length as

$$\frac{\tau}{\rho} = \ell^2 \left| \frac{\partial u}{\partial y} \right| \frac{\partial u}{\partial y} \qquad \text{B-1}$$

or equivalent turbulent viscosity as

$$\nu_t = \ell^2 \left| \frac{\partial u}{\partial y} \right| \qquad \text{B-2}$$

in which the mixing length ℓ is assumed in the form of a ramp function (Figure B-1).

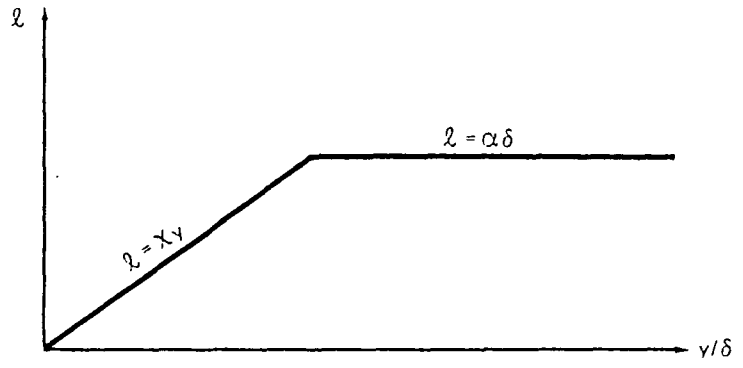


Figure B-1

where δ is the displacement thickness, y - distance normal to the wall and χ = 0.4 is the Von Karman constant.

There have been numerous attempts to extend the mixing length formula $\ell = \chi y$ to include the viscous sublayer by modifying ℓ. Van Driest proposed the following modification

$$\ell = \chi y \left(1 - e^{-y/A}\right) \qquad \text{B-3}$$

where A is a damping wall constant calculated as

$$A = A^+ \frac{\nu}{U_\tau}$$

and where ν is the kinematic laminar viscosity,

$U_\tau \equiv \sqrt{\tau_{w/\rho}}$ is "friction velocity" and

$A^+ = 26$ is an empirical constant which may very with pressure gradient, transpiration, etc.

If we define a characteristic bounday layer distance y^+ as

$$y^+ \equiv \frac{y\sqrt{\tau_W/\rho}}{\nu} = \frac{yu_\tau}{\nu} \qquad \text{B-5}$$

(Note the similarity between y^+ and Re), then the Van Driest formula can be expressed as

$$\ell = \chi y \, (1 - e^{-y^+/A^+}) \qquad \text{B-6}$$

Various research workers have proposed further modifications of Van Driest's exponent argument (arg = y^+/A^+) viz:

Patankar - Spalding	$\arg = -y^+ \tau^{1/2}/A^+$	
Launder - Spalding	$\arg = -y^+ \tau_+/A^+$	B-7
Cebeci - Smith	$\arg = -y^+/A^*$	

where $A^* = A^+ \{\frac{P^+}{u^+}(e^{11.8u^+} - 1) + e^{11.8u^+}\}^{-1/2}$ B-8

$$\tau_\tau = \tau/\tau_w, \; P^+ = \frac{\nu}{\rho u^3}\frac{dp}{dx}, \; u^+ = \frac{u}{u_\tau} \qquad \text{B-9}$$

The Cebeci - Smith model extends the Van Driest formula to flows with significant pressure gradients.

Van Driest formula can also be used to calculate an effective viscosity

$$\mu_{eff} = \nu + \ell^2 \left|\frac{\partial u}{\partial y}\right| = \nu + \chi^2 y^2 \, (1 - e^{-y^+/A^+})^2 \left|\frac{\partial u}{\partial y}\right| \qquad \text{B-10}$$

or in nondimensional form

$$\nu^+ = 1 + \frac{\ell}{\nu}\left|\frac{\partial u}{\partial y}\right| = 1 + \frac{\chi^2 y^2}{\nu}(1 - e^{-y^+/A^+})^2 \left|\frac{\partial u}{\partial y}\right| \qquad \text{B-11}$$

Figure B-2 presents the resulting distribution $\nu^+ \sim y^+$ (see Reference 10).

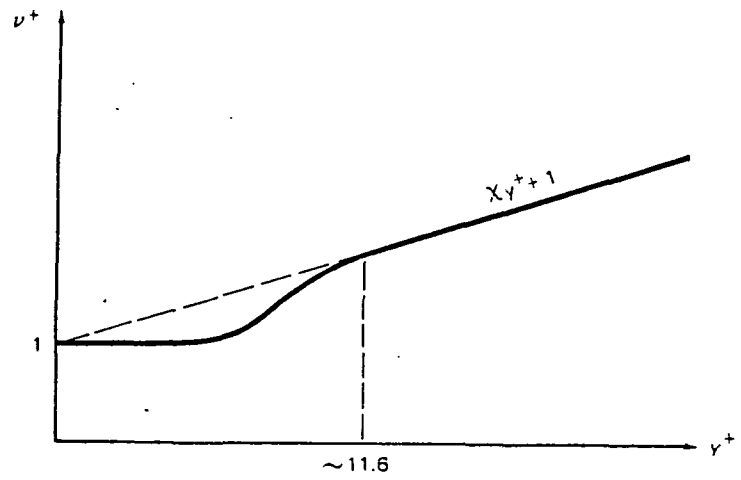


Figure B-2

For $y^+ \geq 11.6$ a simple relation can be established

$$v^+ \to \propto \qquad v^+ = xy^+ \tag{B-12}$$

which will be used as a basis of wall funcitons

Wall Functions

Finite difference schemes used in fluid flow calculations approximate the velocity gradients simply by a linear difference

$$\frac{du}{dy} \simeq \frac{u_{j+1} - u_j}{\Delta y} \tag{B-13}$$

Near the solid boundary where large velocity gradients exist the shear stress (expressed in terms of the velocity gradient)

$$-\tau_w = \mu \frac{\partial u}{\partial y} \simeq \mu_e \frac{u_p}{\Delta y} \tag{B-14}$$

is obtained by solving simplified N-S equations viz:

$$\frac{d}{dy}\left(\mu_{eff}\frac{du}{dy}\right) = \frac{d\tau_w}{dy} + \frac{dp}{dx} \qquad \text{B-15}$$

which after integration yields:

$$\mu_{eff} \cdot \frac{du}{dy} = \tau_w + y\frac{dp}{dx} \qquad \text{B-16}$$

Introducing nondimensional quantities:

$$y^+ = \frac{yu_\tau}{\nu} = \frac{y}{\nu}\frac{u}{u^+}$$

$$u^+ = u/u_\tau$$

$$p^+ = \frac{\nu}{\rho u_\tau^3}\frac{dp}{dx} \qquad \text{B-17}$$

$$\mu^+ = \nu^+ = \frac{\nu eff}{\nu} = 1 + \frac{\nu_\tau}{\nu}$$

$$u_\tau = \sqrt{\tau_w/\rho}$$

we can write equation (B-15) as

$$\frac{du^+}{dy^+} = \frac{1 + p^+y^+}{\nu^+} \qquad \text{B-18}$$

First Case $P^+ = 0$.

If axial pressure gradient is negligible $P^+ = 0$, then integration of equation (B-18) with equation (B-12) i.e. $\nu^+ = \chi y^+$ gives:

$$\int_0^\infty \frac{du^+}{dy^+}\,dy^+ = \int_0^\infty \frac{1}{\chi y^+}\,dy^+ = \frac{1}{\chi}\,\ell n\,(Ey^+) \qquad \text{B-19}$$

where E is the integration constant E = 9 calculated for $u^+ = y^+$ with $y^+ \leq 11.6$ from

$$u^+ = y^+ = \frac{1}{\chi}\,\ell n\,(Ey^+)$$

The expression below is the well known log-law wall function formula

$$u^+ = \frac{1}{\chi} \ln (Ey^+) \qquad \text{B-20}$$

Finally the shear stress is calculated from the relationship

$$\tau_w/\rho = \nu_{eff} \frac{\partial u}{\partial y} = \nu^+ \nu \frac{u_{wall} - u}{\Delta y} \qquad \text{B-21}$$

where ν^+ is obtained from eq. (B-18) with $P^+ = 0$

$$\nu^+ = \frac{dy^+}{du^+} \simeq \frac{y^+}{u^+} \qquad \text{B-22}$$

Second Case $P^+ > 0$:

For flows with significant pressure gradients $P^+ > 0$ an analytical solution of eq. (B-18) viz:

$$\frac{du^+}{dy^+} = \frac{1 + P^+ y^+}{\nu^+} \qquad \text{B-23}$$

has been obtained by Launder and Spalding (Reference 10) in the following form

$$u^+ = \frac{1}{\chi} \left(2\{\sqrt{1 + P^+ y^+} - 1\} + \ln\{\frac{4Ey^+}{2 + P^+ y^+ + 2\sqrt{1 + P^+ y^+}}\}\right. \qquad \text{B-24}$$

where E is a function of P^+ and can be calculated from the above formula with $u^+ = y^+ = 11.6$

The shear stress is calculated similarly as in the first case.

Implementation of the Wall Functions

The previous equation for u^+ is nonlinearly dependent on y^+ and p^+. Therefore we will use deffinitions of y^+, p^+ and u^+ expressed in terms of one common variable s - called the shear rate coefficient

$$s \equiv \frac{\tau_w}{\rho u^2} = \frac{\tau_w}{\rho} \frac{1}{u^2} = \frac{u^2}{u^2 \tau} = \frac{1}{(u^+)^2} \qquad \text{B-25}$$

$$y^+ = \frac{yu}{\nu}\frac{1}{u^+} = \frac{Re}{u^+} = Re\sqrt{s} \qquad \text{B-26}$$

$$p^+ = \frac{dp}{dx}\frac{\mu}{\rho^2}\frac{(u^+)^3}{u^3} = C \cdot (u^+)^3 \qquad \text{B-27}$$

$$p^+y^+ = C(u^+)^3\frac{Re}{u^+} = C \cdot Re\,(u^+)^2 = \frac{c\,Re}{s} \qquad \text{B-28}$$

Before inserting them to u^+ notice that:

$$(1 + \sqrt{1 + p^+y^+})^2 = 2 + p^+y^+ + 2\sqrt{1 + p^+y^+} \qquad \text{B-29}$$

Lets define, for convenience, $a \equiv \sqrt{1 + p^+y^+}$ then u^+ is written as:

$$u^+ = \frac{1}{\chi}(2a - 2 + \ell n\,(4Ey^+) - \ell n\,(1 + a)^2) = \ldots$$

$$= \underbrace{\frac{1}{\chi}\ell n\,(Ey^+)}_{\text{standard wall function formula.}} \underbrace{- \frac{2}{\chi}(2 - \ell n\,2) + \frac{2}{\chi}(1 + a - \ell n\,(1 + a))}_{\text{additional terms due to pressure gradient effects.}} \qquad \text{B-30}$$

APPENDIX C

THE IMPLEMENTATION OF BOUNDARY CONDITIONS IN PHOENICS (EXTRACTED FROM PHOENICS USER CLUB (PUC) NEWSLETTER # 3).

THE PHOENICS IMPLEMENTATION OF BOUNDARY CONDITIONS

1) Introduction

Many people using PHOENICS have trouble with a boundary condition or source description when setting up their SATELLITE. This section will be concerned with the explanation of the concepts behind the PHOENICS boundary conditions. How the correct COEFFICIENT and VALUE are determined will be shown: and examples of frequently encountered boundary conditions will be given. It will be assumed that users are familiar with the subroutines PLACE and COVAL to specify the location and the appropriate coefficient and value for the boundary/source.

2) The General Principle

All boundary conditions are inserted in PHOENICS as sources or sinks of one or more variables. These are represented by linear expressions of the form:

$$S_\Phi = (C_\Phi + [[\ s_m\ ]])\ x\ (V_\Phi - \Phi_P) \qquad (1)$$

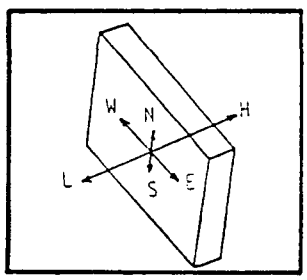
where the mass source s_m is given by:

$$s_m = C_m\ (V_m - P_P)$$

The symbol [[ ]] refers to the use of the upwind practice. the subscript P refers to the centre of the finite-domain cell in question. and C_Φ. V_Φ are referred to as the 'coefficient' and the 'value' for variable Φ. Expression (1) can be used either 'per unit area or volume' or as the total for the cell in question. Equation (1) is easy to understand. if we recall the general form of the PHOENICS finite-domain equations. eg:

$$A_P\ \Phi_P = \sum_i A_i\ \Phi_i + (S_u - S_P\ \Phi_P) \qquad (2)$$

Equation (2) was derived by considering the contributions to the balances over the control volume P of the neighbouring control cells.



For any internal link. in a given control volume P. say the link between point P and its East neighbour. we write the term:

$$A_E\ (\Phi_E - \Phi_P) \qquad (3)$$

where the coefficient A_E represents effects of convection and diffusion added together. Including the links of P with all its neighbours. and collecting terms. we arrive at the general equation (2).

In general. for internal points. the interactions between any two points are expressed by adding the term:

$$a_{link}\ (\Phi_{neighbour} - \Phi_P) \qquad (4)$$

where $a_{link} = D + [[\dot{m}]]$ (5)

D stands for diffusion and $[[\dot{m}]]$ for upwinded convection.

PHOENICS treats boundaries in the same manner as any other points in the field. Therefore. the effect of a boundary on an adjacent cell is expressed by adding to the finite-domain equation a term:

$$a_{link}\ (\Phi_b - \Phi_P) \qquad (6)$$

where Φ_b is the boundary 'value' of Φ. Again:

$$a_{link} = D + [[\dot{m}]]$$

Therefore equation (6) becomes:

$$(D + [[\dot{m}]])\ (\Phi_b - \Phi_P) \qquad (7)$$

which is identical to equation (1) if:

$$C_\phi = 0$$

$$S_m = \dot{m}$$

$$V_\phi = \phi_b$$

Again $[[\dot{m}]]$ symbolises that, in accordance with the 'upwind' principle, only inflow is of influence. Therefore, for the general variable ϕ, the 'coefficient' is simply the diffusive transport of ϕ between the boundary itself and the centre of the adjacent cell.

The convective transport at the boundary $[[\dot{m}]]$ requires special treatment, because PHOENICS does not store the boundary values themselves. Define:

$$\dot{m} = C_m (P_b - P_P) \qquad (8)$$

which simply means that the flow rate is the pressure difference (between an external pressure and the pressure at P) divided by the flow resistance. Thus C_m has the physical significance of the reciprocal of a flow resistance between the internal grid node P, where the pressure is pp, and the external pressure p_b, which we shall denote as V_m (for value for mass) for the purpose of retaining the general concept of 'coefficient and value'.

3) The Finite-Domain Equation for Boundary Cells

The finite-domain equation for boundary cells is the same as equation (2), where one of the neighbours is missing (the one corresponding to the boundary cell face) and where the linearised source $S_U - S_P \phi_P$ contains the additional source/sink due to boundary conditions. Thus, the equation becomes:

$$(A_P + S_P + C_\phi)\phi_P = \sum_{\substack{i \\ \text{except boundary}}} A_i p_P + S_U + C_\phi V_\phi \qquad (9)$$

The pressure-correction equation becomes:

$$(A_P + C_m) p'_P = \sum_{\substack{i \\ \text{except boundary}}} A_i p'_P + C_m V_m + E \qquad (10)$$

where E is the mass error.

4) The Treatment of Various Boundary Conditions According to the Above Formulation

(i) Special Cases

(a) Fixed Source of Mass, Regardless of Pressure

Set:

$$C_m = 1.E-10, \quad V_m = S_m * 1/C_m$$

where S_m is the desired source of mass. This is a direct consequence of equation (8) since:

---

* See note in Section 7

$$\dot{m} = S_m = C_m (V_m - P_P) = 1.E-10 * (S_m * 1.E10 - P_P)$$
$$= S_m - 1.E-10\ P_P \simeq S_m$$

(b) Fixed External Pressure Regardless of Mass Flow:

Set:

$$C_m = 1.E10, \quad V_m = p^*$$

where p^* is the desired value of pressure. This case will be discussed further in the next section.

(c) Fixed Value of Any Dependent Variable, ϕ

Set:

$$C_\phi = 1.E10, \quad V_\phi = \phi^*$$

where ϕ^* is the desired value of ϕ. This is a direct consequence of equation (9) since:

$$\phi_P = \frac{\sum A_i \phi_i + Su + 1.E10 * \phi^*}{A_P + S_P + 1.E10}$$

The 1.E10 terms are much larger than the other terms and therefore:

$$\phi_P \simeq \frac{1.E10 * \phi^*}{1.E10} = \phi^*$$

(II) Treatment of Various Practical Boundary Conditions

(a) Linear Source (For Example Wall Heat Transfer)

$$S_h = \dot{q}''_{wall} = a\,(T_{wall} - T_p) = a/c_p\,(c_p T_{wall} - h_p)$$

where a = heat-transfer coefficient. Therefore:

$$C_h = a/c_p; \quad V_h = c_p T_{wall}.$$

(b) Non-Linear Source (For Example Internal Resistance)

* Distributed resistance:

$$S_w = K_{dr}\,\rho w^2\,A.\,\delta z \quad (\text{ie } \partial p/\partial z = K_{dr}\,\rho w^2)$$

Then: $C_w = K_{dr}\,\rho w\,A\,\delta z, \quad V_w = 0$

* Baffle:

$$S_w = K_b\,\rho w^2\,A \quad (\text{ie } \Delta p = K_b\,\rho w^2)$$

Then: $C_w = K_b\,\rho w\,A, \quad V_w = 0$

* Pressure-drop per row of rods in cross flow

$$\Delta p_{cell} = K\ 1/2\ \rho w^2\ N, \text{ where N is the number of rows}$$

$$S_{w,total} = K\ 1/2\ \rho w^2\ A\ N$$

Then: $C_w = K\ 1/2\ \rho w\ A\ N, \quad V_w = 0$

5) The Inflow Boundary

Fixed mass flow ($\dot{m}$): applicable in both single and two phase flows).
Set:

$$C_m = 1.E\text{-}10, \quad V_m = \dot{m}$$

Also set V_ϕ's for all ϕ's. this is because a flow rate of $\dot{m}$ carries into the domain the boundary values of all ϕ's: for example it carries in w-momentum equal to $\dot{m}w_{in}$. energy. $\dot{m}h_{in}$. etc.

In circumstances where convective transport across the boundary is dominant. C_ϕ would be set to zero. This is usually the case. If it is desired to include diffusive. as well as convective. transport. C_ϕ would be set to the appropriate finite value Γ/δ. where Γ is the diffusive transport coefficient and δ the distance between the boundary and the first internal grid node.

6) The Outflow Boundary

Usually the specification of a fixed-pressure boundary condition is *adequate. This is achieved by setting:*

$$C_m = \text{"large"}, \quad V_m = \text{required } p_{ext}$$

This boundary condition setting has the meaning that the outflow is discharging in a reservoir of uniform pressure p_{ext} and leads to pp's (at the last grid node before the outflow) such that the expression

$$\dot{m} = C_m\,(p_p - p_{ext})$$

provides the correct flow-rate (satisfying overall continuity). Users familiar with recent finite-element techniques would recognize this practice as the 'penalty method'.

Caution must be exercised in choosing the "large" value for C_m. particularly when p_{ext} is not equal to zero: for it is quite possible. if C_m is too large. for the value of $(p - p_{ext})$ for the required outflow (or inflow) rate to be so small compared with the value of p_{ext} as to be of the order of. or less than. the precision of the computer storage. This can result in large errors in the evaluation of $(p - p_{ext})$ and hence of the flow rate. which can adversely affect the *solution.*

In general, for the case of a fixed external pressure, C_m would be prescribed to give the required dependence of the flow rate on pressure difference. Thus, if C_m were set to 1.0, then a pressure difference (p_{ext} - p) of 1 Nm^{-2} would cause an inflow rate of 1.0 kgs^{-1} or $kgs^{-1}.m^{-2}$ depending on the setting of type). A good rule is to set C_m to be of the order of:

$$1000 * (\text{expected mass-flow rate} / p_{ext}).^*$$

To specify a known resistance or pressure drop at outlet set:

$$C_m = \frac{\dot{m}}{\Delta p} \quad , \quad V_m = p_{ext}$$

The rule is slightly different for two phase flows. For an outflow (ie $C_{m,i}$ ($V_{m,i}$ - p) < 0.0) the outflow is multiplied by R_i and ρ_i to become:

$$\rho_i R_i C_{m,i} (V_{m,i} - p);$$

where ρ_i and R_i are the local values of density and volume fraction of the phase. This ensures that, if the values of $C_{m,i}$ and $V_{m,i}$ are the same for both phases, the outflows of each phase from a cell are in proportion to the mass concentrations of the phases in the cell, as is physically reasonable.

7) Note

When using the subroutine COVAL several FORTRAN variables have been provided to simplify the input. These include:

FIXFLU (= 1.E-10)
FIXVAL (= 1.E10)
ONLYMS (= 0.0)

If FIXFLU or 1.E-10 is used in the call to COVAL the multiplicaton of the value by 1.E10 is done by COVAL and therefore should not be done by the user.

---

* This formula is very approximate and the coefficient found may need further adjustment - by up to ±2 orders of magnitude to give the correct flow behaviour.

APPENDIX D

THE EQUILIBRIUM CHEMISTRY MODEL FOR H_2 - O_2 SYSTEM

(Based on N.C. Markatos, D.B. Spalding and D.G. Tatchell "Combustion of Hydrogen Injected into a Supersonic Airstream", NASA CR - 2802, 1977).

Appendix D

THE EQUILIBRIUM CHEMISTRY FOR H_2 - O_2 SYSTEM

The equilibrium chemistry model used to predict the properties of hydrogen-oxygen flame can be expressed by the four following reactions.

$$H + H \underset{\leftarrow}{\overset{k_1}{\rightleftharpoons}} H_2 \qquad \text{D-1}$$

$$O + O \underset{\leftarrow}{\overset{k_2}{\rightleftharpoons}} O_2 \qquad \text{D-2}$$

$$H + OH \underset{\leftarrow}{\overset{k_3}{\rightleftharpoons}} H_2O \qquad \text{D-3}$$

$$O + H \underset{\leftarrow}{\overset{k_4}{\rightleftharpoons}} OH \qquad \text{D-4}$$

There are six species involved in these reactions and only two atomic elements viz H and O. Mas balance relations provide two basic equations in the form of total atomic mass fractions for O and H:

$$F = m_{O_2} + m_O + \frac{W_O}{W_{H_2O}} m_{H_2O} + \frac{W_O}{W_{OH}} m_{OH} \qquad \text{D-5}$$

$$f = m_{H_2} + m_H + \frac{W_{H_2}}{W_{H_2O}} m_{H_2O} + \frac{W_H}{W_{OH}} m_{OH} \qquad \text{D-6}$$

where F is the total mass fraction of oxygen in any form and f is the total mass fraction of hydrogen in any form. In H_2 - O_2 flames the following relation holds:

$$f + F = 1 \qquad \text{D-7}$$

Therefore if F is known, f can be determined.

From thermodynamic considerations the equilibrium constant K_p, for the reaction:

$aA + bB \underset{}{\overset{K_p}{\rightleftharpoons}} cC$ is defined by,

$$K_p = \frac{x_C^c}{x_A^a \, x_B^b} p^{c-a-b} \qquad (D\text{-}8)$$

where x stands for concentration and the pressure p is in atmospheres. For each of the four reactions (D-1) to (D-4) in the present model c-a-b = -1. Expressing the concentrations in terms of mass fractions by noting that,

$$m_i = \frac{Wi}{W} x_i \qquad (D\text{-}9)$$

where W is the molecular weight of the mixture we get:

$$K_p' = K_p p W \frac{W_C^c}{W_A^a \, W_B^b} = \frac{m_C^c}{m_A^a \, m_B^b} \qquad (D\text{-}10)$$

Thus the equilibrium equations for the reactions (D-1) to (D-4) can be written:

$$K_1' = \frac{m_{H_2}}{m_H^2} \qquad (D\text{-}11)$$

$$K_2' = \frac{m_{O_2}}{m_O^2} \qquad (D\text{-}12)$$

$$K_3' = \frac{m_{H_2O}}{m_H m_{OH}} \qquad (D\text{-}13)$$

$$K_4' = \frac{m_{OH}}{m_O m_H} \qquad (D\text{-}14)$$

The condition of equilibrium is expressed using four equilibrium constants for the four chemical reactions. If thermodynamic equilibrium prevails, the K's take values which depend upon temperature alone. In the above set of equations there are seven unknowns (m_{H_2}, m_{O_2}, m_H, m_O, m_{OH},

m_{H_2O} and F; f being given) and seven equations (D-5, D-6, D-7 D-11, D-12, D-13, D-14). The problem is therefore soluble. The remaining discussion defines the solution procedure.

Derivation of Solution Procedure

The present procedure is based on the reduction of the number of variables under consideration. Two equations are derived as follows:

Equations (D-11 to D-14) ,are solved to give the relationships:

$$m_H = \frac{1}{\sqrt{K_1'}} \sqrt{m_{H_2}} \qquad \text{(D-15)}$$

$$m_O = \frac{1}{\sqrt{K_2'}} \sqrt{m_{O_2}} \qquad \text{(D-16)}$$

$$m_{H_2O} = \frac{K_3' K_4'}{K_1' \sqrt{K_2'}} m_{H_2} \sqrt{m_{O_2}} \qquad \text{(D-17)}$$

$$m_{OH} = \frac{K_4'}{\sqrt{K_1' K_2'}} \sqrt{m_{H_2}} \sqrt{m_{O_2}} \qquad \text{(D-18)}$$

It is convenient to define the following parameters which depend upon temperature alone and therefore, can be tabulated right at the begining.

$$\bar{A} = \frac{1}{\sqrt{K_1'}} \qquad \text{(D-19)} \qquad \bar{C} = \frac{K_3' K_4'}{K_1' \sqrt{K_2'}} \qquad \text{(D-21)}$$

$$\bar{B} = \frac{1}{\sqrt{K_2'}} \qquad \text{(D-20)} \qquad \bar{D} = \frac{K_4'}{\sqrt{K_1' K_2'}} \qquad \text{(D-22)}$$

Using equations (D-15 to D-18) to eliminate m_O, m_{H_2O}, m_H and m_{OH} from equations (D-5) and D-6) gives:

$$F = m_{O_2} + \sqrt{m_{O_2}} \left(\bar{B} + \frac{8}{9} \bar{C} m_{H_2} + \frac{16}{17} \bar{D} \sqrt{m_{H_2}}\right) \tag{D-23}$$

$$f = m_{H_2} \left(1 + \frac{1}{9} \bar{C} \sqrt{m_{O_2}}\right) + \sqrt{m_{H_2}} \left(\bar{A} + \frac{1}{17} \bar{D} \sqrt{m_{O_2}}\right) \tag{D-24}$$

where the definitions given by equations (D-13 to D-22) have been used.

These equations have the form of a quadratic equation:

$$\bar{a}u^2 + \bar{b}u + \bar{c} = 0$$

which yield the solution:

$$u = \frac{-2\bar{c}}{\bar{b} \pm \sqrt{\bar{b}^2 - 4\bar{a}\bar{c}}} \tag{D-25}$$

Note that $\bar{a}$ and $\bar{b}$ are always positive and $\bar{c}$ is always negative. Since $u > 0$, the physically meaningful root is the one with the positive sign. This particular form of quadratic expression is chosen since it does not require subtraction and gives greater precision. Using equation (D-25) to express the solution of equations (D-23) and (D-24) gives:

$$\sqrt{m_{O_2}} = \frac{F}{\left[\frac{\bar{B} + \frac{8}{9} \bar{C} m_{H_2} + \frac{16}{17} \bar{D} \sqrt{m_{H_2}}}{2}\right] + \sqrt{\left[\frac{\bar{B} + \frac{8}{9} \bar{C} m_{H_2} + \frac{16}{17} \bar{D} \sqrt{m_{H_2}}}{2}\right]^2 + F}} \tag{D-26}$$

$$\sqrt{m_{H_2}} = \frac{f}{\left[\frac{\bar{A} + \frac{1}{17} \bar{D} \sqrt{m_{O_2}}}{2}\right] + \sqrt{\left[\frac{\bar{A} + \frac{1}{17} \bar{D} \sqrt{m_{O_2}}}{2}\right]^2 + \left(1 + \frac{1}{9} \bar{C} \sqrt{m_{O_2}}\right) f}} \tag{D-27}$$

Equations (D-26) and (D-27) contain the unknowns m_{O_2} and m_{H_2}, which can be easily determined, now.

APPENDIX E

LISTINGS OF SATELLITE AND GROUND FOR SSME NOZZLE TEST CASE

Listings of SATELLITE includes:

Listing of GROUND includes:

```
C-----------------------  ----------------------  ----------------------
C---=  GROUP 3. Y-DIRECTION :
C      NX<1>,XULAST<1.0>,XFRAC(1-30)
       XFRAC(1)=1.
C-----------------------  ----------------------  ----------------------
C---   GROUP 4. Y-DIRECTION :
C      NY<1>,YVLAST<1.0>,YFRAC(1-30),RINNER,SNALFA
       NY=20
       POWER=1.5
       THROAT=.13088
       YFRAC(NY)=1.
       DO 400 IY=1,NY-1
  400  YFRAC(NY-IY)=1.-(FLOAT(IY)/FLOAT(NY))**POWER
       WRITE(6,2847) (YFRAC(IY),IY=1,NY)
 2847  FORMAT(" YFRAC"/(1P5E11.3))
C-----------------------  ----------------------  ----------------------
C---   GROUP 5. Z-DIRECTION :
C      NZ<1>,ZWLAST<1.0>,ZFRAC(1-30)
C---NZMAX=47
       NZ=40
       NZT=6
       NTAB=393
       NTABT=31
C---READ IN NOZZLE GEOMETRY DATA FROM FILE NOZZLE.DTA--------
       OPEN(25,FILE='NOZZLE.DTA',ACCESS='SEQUENTIAL',STATUS='OLD'
      1 ,FORM='FORMATTED',ERR=999)
       READ(25,*) OZZLE
       ZFRAC(NZ)=OZZLE(NTAB,1)-OZZLE(1,1)
       ZFRAC(NZT)=OZZLE(NTABT,1)-OZZLE(1,1)
C---ZFRACS UP TO THROAT---
       POWER1=1.5
       FNZ=FLOAT(NZT)
       DO 500 IZ=1,NZT-1
       ZFRAC(NZT-IZ)=(1.-(FLOAT(IZ)/FNZ)**POWER1)*ZFRAC(NZT)
  500  CONTINUE
C---ZFRACS DNS. OF THROAT--
       POWER2=2.
       FZNOZ=FLOAT(NZ-NZT)
       ZNOZ=ZFRAC(NZ)-ZFRAC(NZT)
       DO 501 IZ=NZT+1,NZ-1
  501  ZFRAC(IZ)=ZFRAC(NZT)+(FLOAT(IZ-NZT)/FZNOZ)**POWER2*ZNOZ
C--ADD AN ADDITIONAL CELL DNS. OF EXIT PLANE.
        ZCLAST=2.*(ZFRAC(NZ)-ZFRAC(NZ-1))
        ZFRAC(NZ+1)=ZFRAC(NZ)+ZCLAST
       NZ=NZ+1
       WRITE(6,6723) (ZFRAC(IZ),IZ=1,NZ)
 6723  FORMAT(" ZFRAC"/(1P5E11.3))


C-----------------------  ----------------------  ----------------------
C---   GROUP 6. MOVING GRID OR DISTORTED (BODY-FITTED) GRID :
C                ---- DISTORTED (BODY-FITTED) GRID :
C      ND,
C      XE(1-NYP1,1-NZP1,1-ND)<(NYP1*NZP1*ND)*1.0>,
C      XU(1-NYP1,1-NZP1,1-ND),
C      YN(1-NXP1,1-NZP1,1-ND)<(NXP1*NZP1*ND)*1.0>,
C      YS(1-NXP1,1-NZP1,1-ND),
C      ZH(1-NXP1,1-NYP1,1-ND)<(NXP1*NYP1*ND)*1.0>,
C      ZL(1-NXP1,1-NYP1,1-ND),STORSA(1-6)<6*.F.>,STORND(1-6)<6*.F.>,
C      STORP<.F.>,STORPE<.F.>,STORPN<.F.>,STORPH<.F.>,PRTBPC<.F.>,
C      DARCY
```

```
C     *NOTES FOR VELOCITY-FIELD PRINTOUT
C      (1) THE STANDARD VELOCITY-FIELD PRINTOUT IS FOR THE
C          VELOCITY RESOLUTES AND IS ACTIVATED IN THE USUAL
C          WAY.
C      (2) AN ADDITIONAL OPTION EXISTS FOR PRINTING THE
C          CARTESIAN VELOCITY-COMPONENTS WHICH MAY BE
C          ACTIVATED BY SETTING THE FOLLOWING LOGICALS:
C              A) STOVAR(U2)=.T. FOR U-COMPONENT
C              B) STOVAR(V2)=.T. FOR V-COMPONENT
C              C) STOVAR(W2)=.T. FOR W-COMPONENT
C     *WARNING!!!!!!
C       WHEN USING BFCS PLEASE NOTE THAT STOVAR(H3),STOVAR(C4)
C       AND STOVAR(21) ARE UNAVAILABLE.
C     *USER SETS ND (NUMBER OF SUB-DOMAINS) HERE:
      BFC=.TRUE.
      ND=1
      STORSA(3)=.TRUE.
      STORWD(3)=.TRUE.
      STORSA(4)=.TRUE.
      STORSA(5)=.TRUE.
      STORSA(6)=.TRUE.
      STUCRN=.FALSE.
      CALL DOMAIN(1,1,NX,1,NY,1,NZ)
      IZTAB=1
      Z=OZZLE(IZTAB,1)
      Y=OZZLE(IZTAB,2)
      DO 601 IZ=1,NZP1
      IF(IZ.EQ.1) THEN
      YNN=Y
      GO TO 600
      ELSE IF(IZ.EQ.NZ) THEN
      DIVV=OZZLE(NTAB,2)-YNN
      YNN=OZZLE(NTAB,2)
      GO TO 600
      ELSE IF(IZ.EQ.NZP1) THEN
      YNN=YNN+DIVV
      GO TO 600
      END IF
      ZZZ=ZFRAC(IZ-1)-ZFRAC(NZT)
  104 IZTAB=IZTAB+1
      IF(IZTAB.GT.NTAB) GO TO 601
      ZLAST=Z
      YLAST=Y
      Z=OZZLE(IZTAB,1)
      Y=OZZLE(IZTAB,2)
      IF(Z+.000001.LT.ZZZ) GO TO 104
      YNN=YLAST+(ZZZ-ZLAST)*(Y-YLAST)/(Z-ZLAST)
  600 DO 602 IX=1,NXP1
      YN(IX,IZ,1)=YNN*THROAT
  602 YS(IX,IZ,1)=0.
  601 CONTINUE
      DO 605 IY=1,NYP1
      DO 604 IZ=1,NZP1
      IF(IY.EQ.1) THEN
      XXE=0.
      ELSE
      XXE=.01*YFRAC(IY-1)*YN(1,IZ,1)
      END IF
      XE(IY,IZ,1)=XXE
  604 XW(IY,IZ,1)=-XXE
      DO 606 IX=1,NXP1
      ZH(IX,IY,1)=ZFRAC(NZ)*THROAT
  606 ZL(IX,IY,1)=0.
  605 CONTINUE
```

```
C-------------------- ---------- ----------
C---  GROUP 8.DEPENDENT VARIABLES TO BE SOLVED FOR OR STORED :
C      SOLVAR(1-25)<25*.F.>,STOVAR(1-25)<25*.F.>.CONC1(1-4)<4*.T.>
C      USE FOLLOWING NAMED INTEGERS FOR ARRAY ELEMENTS 1-20:
C      P1.PP.U1.U2.V1.V2.W1.W2.M1.M2.RS.KE.EP.H1.H2.H3.C1.C2.C3.C4.
       SOLVAR(P1)=.TRUE.
       SOLVAR(PP)=.TRUE.
       SOLVAR(V1)=.TRUE.
       SOLVAR(W1)=.TRUE.
       SOLVAR(C1)=.TRUE.
       SOLVAR(KE)=.TRUE.
       SOLVAR(EP)=.TRUE.
       SOLVAR(H1)=.TRUE.
       STOVAR(23)=.TRUE.
       STOVAR(H2)=.TRUE.
       STOVAR(U2)=.TRUE.
       STOVAR(V2)=.TRUE.
       STOVAR(W2)=.TRUE.
C----- EXTRA STORAGE FOR CONTRAVARIANT VELOCITY COMPONENTS
       STOVAR(16)=.TRUE.
       STOVAR(21)=.TRUE.
C-------------------- ---------- ----------
C---  GROUP 9. VARIABLE LABELS :
C      TITLE(1-25)<2HP1.2HPP.2HU1.2HU2.2HV1.2HV2.2HW1.2HW2.2HR1.
C      2HR2.2HRS.2HKE.2HEP.2HH1.2HH2.2HH3.2HC1.2HC2.
C      2HC3.2HC4.2HRX.2HRY.2HRZ.  2*4H****>
       TITLE(2 )=4HRHO1
       TITLE(H2)=4HTEMP
       TITLE(23)=4HCERR
C-------------------- ---------- ----------
C---  GROUP 10 PROPERTIES:
C      IRHO1<1>,IRHO2<1>,RHO1<1.0>,RHO2<1.0>.
C      ARHO1<1.0>,BRHO1<1.0>,CRHO1<1.0>
C      IEMU1<1>,EMU1<1.0>,EMULAM<1.E-10>
C      IHSAT,H1SAT,H2SAT,PSATEX<1.0>
C      SIGMA(1-25)<1.0,2.0,1.,1.E10,1.,1.E10,1.,1.E10.
C      4*1.0,1.314,1.0,1.E10,10*1.0>
       SIGMA(24)=.7
       SIGMA(14)=.88
       EMULAM=1.02E-4
       EMU1=EMULAM
       IRHO1=-1
C MOLAR NUMBERS:   SC(1) FOR H2O      SC(2) FOR H2      SC(3) FOR O2
C MASS FRACTIONS: SMO(1) FOR H2O     SMO(2) FOR H2     SMO(3) FOR O2
       FMIX=6.054851
       SMO(1)=0.
       SMO(2)=1./(1.+FMIX)
       SMO(3)=1.-SMO(2)
       ENTHMX=-5.7768E5
       WRITE(6,6783) SMO(1),SMO(2),SMO(3)
 6783 FORMAT("  H2O(0) H2(0) O2(0) ",1P3E12.4)
```

```
C------ SELECT COMPOSITION TO MATCH ADIABATIC TEMPERATURE
      DO 1777 ITRY=1,1
      H2OAD=.0434175+1.E-7*FLOAT(ITRY-1)
      SMB(1)=SMO(1)+H2OAD
      SMB(2)=SMO(2)-H2OAD/9.
      SMB(3)=SMO(3)-H2OAD*8./9.
C---MASS FRACTION/MOL WT OR MOLES/UNIT MASS.
      SC(1)=SMB(1)/18.
      SC(2)=SMB(2)/2.
      SC(3)=SMB(3)/32.
      TEMPO=300.
      CALL ENTHAL(TEMPO,ENTH,CPDR,SC,3)
      HHH=ENTH*TEMPO*RGAS
      EEE=CPDR*RGAS*TEMPO
      WRITE(6,6749) SC(1)*18.,SC(2)*2.,SC(3)*32.,TEMPO,CPDR*RGAS,
     1                HHH,EEE,HHH-EEE
 6749 FORMAT(" ASSUMED INLET COMPOSITION AND TEMPERATURE"/
     1 " M(H2O)=",1PE12.4," M(H2)= ",1PE12.4," M(O2)= ",1PE12.4/
     2 " TO CP H E HO",1P6E12.4)
      WRITE(6,1519) H2OAD,ENTHMX,HHH
 1519 FORMAT("H2OAD EX EE ",1P3E12.4)
 1777 CONTINUE
C
      FMOR=2.*SC(2)
C----MIXTURE AFTER COMBUSTION-----------------------------------
      SC(1)=SC(1)+2.*SC(3)
      SC(2)=SC(2)-2.*SC(3)
      SC(3)=0.
      FMFR=2.*SC(2)
      TTEMPR=TEMPO
      CALL TEMPER(HHH,TTEMPR,TEMP,CPDR,RGAS,SC,3)
      WRITE(6,6709) TTEMPR,TEMP,HHH
 6709 FORMAT("TEMPER FOUND TO T H",1P3E12.4)
      CALL ENTHAL(TEMP,ENTH,CPDR,SC,3)
      WRITE(6,6751) TEMP,ENTH,ENTH*RGAS*TEMP
 6751 FORMAT("T ENT H ",1P3E12.4)
      WRITE(6,4750) SC(1)*18.,SC(2)*2.,SC(3)*32.
 4750 FORMAT(" FULLY BURNED COMPOSITION AND ADIABATIC TEM SELECTION
     1 /" M(H2OR)=",1PE12.4," M(H2R)=",1PE12.4," M(O2R)= ",1PE12.4
C---MEAN MOLECULAR WEIGHT      AND ENTHALPY
      WTMOL=(SC(1)*18.+SC(2)*2.)/(SC(1)+SC(2))
      H2SAT=RGAS*ENTH
C---CHAMBER AREA
      RCHAM=.2267
      AINLET=RCHAM**2*3.14159
      FLOWA1=AMASF/AINLET
C--- A/A*  AT INLET
      AAT=OZZLE(1,2)**2
      AM=0.
      CALL MSOLV(GA,0,AAT,AM,S,TTT,PTP,RTR,VRT,ORT)
      TTOT=TEMP
      PTOT=FLOWA1*SQRT(TTOT/WTMOL)/ORT
      PTOT=2935.7 * 6894.757
      WFAC=SQRT(TTOT/WTMOL)
C---INLET VELOCITY
      WIN=VRT*WFAC
      WRITE(6,6744) WIN,TTOT,PTOT
 6744 FORMAT(" WIN =",1PE12.4," TTOT PTOT",1P2E12.4)
C---TOTAL ENTHALPY
      H1SAT=TTOT*H2SAT
      WRITE(6,6497) AAT,AM,TTT,PTP,RTR,VRT,ORT,TTOT,H1SAT,H2SAT,
     1 WTMOL,(SC(II),II=1,3)
 6497 FORMAT("AAT     AM      TTT      PTP       RTR       VRT      ORT"/
     1 1P7E12.4/"  TTOT     H1SAT      H2SAT      WMOL      SC1,2,3"/
     2 1P7E12.4)
```

```
C---OUTLET PRESSURE---
      AAT=OZZLE(NTAB,2)**2
      AM=2.
      CALL MSOLV(GA,1,AAT,AM,S,TTT,PTP,RTR,VRT,ORT)
      POUT=PTOT/PTP
      WRITE(6,6297) AAT,AM,TTT,PTP,RTR,VRT,POUT
 6297 FORMAT("AAT       M        TTT       PTP     RTR         VRT    POUT",
     1 /1P7E12.4)
C--------------------   ---------------   ------------------
C---  GROUP 11 INTER-PHASE TRANSFER PROCESSES :
C     ICFIP,CFIPS,IMDOT,CMDOT,CA1I<1.E6>,CA2I<1.E6>
C--------------------   ---------------   ------------------
C---  GROUP 12 SPECIAL SOURCES :
C     ISPCS0(1-25),AGRAVX,AGRAVY,AGRAVZ,ABUOY,HREF
C--------------------   ---------------   ------------------
C---  GROUP 13 INITIAL FIELDS :
C     FIINIT(1-25)<25*1.E-10>
      FIINIT(P1)=10101.
      FIINIT(W1)=10101.
      IF(SOLVAR(C1)) FIINIT(C1)=10101.
      FIINIT(H1)=H1SAT
      FIINIT(H2)=10101.
C------ FOR INITIAL FIELDS FOR K AND E SEE BOTTOM OF CH.14
C--------------------   ---------------   ------------------
C---  GROUP 14 BOUNDARY/INTERNAL CONDITIONS :
C     ILOOP1,ILOOPN,XCYCLE<.F.>,PBAR,REGION(1-10)<10*.T.>
C    *N.B. ALL 10 REGIONS ARE DEFAULTED .TRUE.,  THE USER SHOULD
C     SET REGION(I)=.FALSE. FOR UNUSED REGIONS 'I'.
      DO 140 IR=1,10
  140 REGION(IR)=.FALSE.
C--------------------   ---------------   ------------------
C---  GROUP 15 TO 24; REGIONS 1 TO 10
C---  ONLY THOSE REGIONS ARE ACTIVE WHICH ARE SPECIFIED BY THE
C     USER, PREFERABLY BY WAY OF:-
C     CALL PLACE(IREGN,TYPE,IXF,IXL,IYF,IYL,IZF,IZL) &
C     CALL COVAL(IREGN,VARBLE,COEFF,VALUE)
      CALL PLACE(1,LOW,1,1,1,20,1,1)
C     CALL COVAL(1,M1,FIXFLU,FLOWA1)
      CALL COVAL(1,M1, .05 ,PTOT)
      IF(SOLVAR(C1)) WIN=WIN*TEMP0/TTOT
      CALL COVAL(1,W1,ONLYMS,WIN)
      IF(SOLVAR(C1)) CALL COVAL(1,C1,ONLYMS,FMUB)
      IF(SOLVAR(H1)) CALL COVAL(1,H1,ONLYMS,H1SAT)
      CALL PLACE(2,HIGH,1,1,1,20,NZ,NZ)
      CALL COVAL(2,M1,.05,POUT-2000.)
      IF(SOLVAR(KE)) THEN
      TURBLV=.1
      SLENTH=.02*THROAT*(OZZLE(1,2))
      EKIN=.5*(WIN*TURBLV)**2
      EPIN=.1643*EKIN**1.5/SLENTH
      WRITE(6,5431) EKIN,EPIN
 5431 FORMAT(" EKIN EPIN ",1P2E12.4)
C     CALL PLACE(3,NORTH,1,1,NY,NY,1,NZ)
C     CALL COVAL(3,W1,WALL,0.)
C----- H1 VALUE WILL BE OVERRITEN IN GROUND
C     CALL COVAL(3,H1,WALL,1.)
      CALL COVAL(1,KE,ONLYMS,EKIN)
      CALL COVAL(1,EP,ONLYMS,EPIN)
C---  INITIAL FIELDS FOR K AND E
      FIINIT(KE)=EKIN
      FIINIT(EP)=EPIN
      END IF
```

```
C-----------------------  ----------------  ----------------------------------
C---  GROUP 25 GROUND STATION :
C     GROSTA<.F.>,NAMLST<.F.>
C    *NAMLST ACTIVATES NAMELIST IN GROUND.
C-----------------------  ----------------  ----------------------------------
C---  GROUP 26 SOLUTION TYPE AND RELATED PARAMETERS :
C     UNOLEP<.F.>,SUBPST<.F.>,DONACC<.F.>
C----- LOGIC(87) SET TO .TRUE. FOR COMPRESSIBLE FLOWS
      LOGIC(87)=.TRUE.
C-----------------------  ----------------  ----------------------------------
C---  GROUP 27 SWEEP AND ITERATION NUMBERS :
C     FSWEEP<1>,LSWEEP<1>,LITHYD<1>,LITC<1>,LITKE<1>,LITH<1>,
C     LITER(1-25)<9*1,-1,15*1>
C     IVELF<1>,NVEL<1>,IVELL<10000>,
C     IKEF<1>,NKE<1>,IKEL<10000>,
C     IENTF<1>,NENT<1>,IENTL<10000>,
C     ICNCF<1>,NCNC<1>,ICNCL<10000>,
C     IRHO1F<1>,NRHO1<1>,IRHO1L<10000>,
C     IRHO2F<1>,NRHO2<1>,IRHO2L<10000>
      FSWEEP=401
      LSWEEP=450
C-----------------------  ----------------  ----------------------------------
C---  GROUP 28 TERMINATION CRITERIA :
C     ENDIT(1-25)<9*1.E-10,0.5,15*1.E-10>
C-----------------------  ----------------  ----------------------------------
C---  GROUP 29 RELAXATION  :
C     RLXP<1.>,RLXPXY<1.>,RLXPZ<1.>,RLXRHO<1.>,RLXMUT<1.>,
C     DTFALS(3-25)<23*1.E10>
      RLXP=.6
      RLXPZ=.6
      RLXPXY=.6
      DTFALS(N1)=1.E3*THROAT
      DTFALS(V1)=DTFALS(W1)
C-----------------------  ----------------  ----------------------------------
C---  GROUP 30 LIMITS :
C     VELMAX<1.E10>,VELMIN<-1.E10>,RHOMAX<1.E10>,RHOMIN<1.E-10>,
C     TKEMAX<1.E10>,TKEMIN<1.E-10>,EMUMAX<1.E10>,EMUMIN<1.E-10>,
C     EPSMAX<1.E10>,EPSMIN<1.E-10>,AMDTMX<1.E10>,AMDTMN<-1.E10>
C-----------------------  ----------------  ----------------------------------
C---  GROUP 31 SLOWING DEVICES : SLORHO<1.>,SLOEMU<1.>
      SLORHO=.3
C-----------------------  ----------------  ----------------------------------
C---  GROUP 32 PRINT-OUT OF VARIABLES :
C     PRINT(1-25)<.T.,.F.,23*.T.>,SUBWGR<.F.>
      PRINT(23)=.TRUE.
      PRINT(2)=.TRUE.
      PRINT(H2)=.TRUE.
      IZMON=12
      IYMON=19
C-----------------------  ----------------  ----------------------------------
C---  GROUP 33 MONITOR PRINT-OUT :
C     IXMON<1>,IYMON<1>,IZMON<1>,NPRMON<1>,NPRMNT<1>
C-----------------------  ----------------  ----------------------------------
C---  GROUP 34 FIELD PRINT-OUT CONTROL :
C     NPRINT<100>,NTPRIN<100>,NXPRIN<1>,NYPRIN<1>,NZPRIN<1>,
C     IZPRF<1>,ISTPRF<1>,IZPRL<10000>,ISTPRL<10000>
C     NUMCLS<10>,KOUTPT
      NPRINT=200
      NYPRIN=2
      KOUTPT=-1
C-----------------------  ----------------  ----------------------------------
C---  GROUP 35 TABLE CONTROL :
C     TABLES<.F.>,NTABLE,NTABVR,LINTAB,NPRTAB,NMON,
C     ITAB(1-8),MTABVR(1-8)
```

```
C---------------------  ---------------  ---------------------
C      GROUP 36-38 ARE NOT DOCUMENTED IN THE INSTRUCTION
C      MANUAL AND ARE INTENDED FOR MAINTENANCE PURPOSES ONLY
C---   GROUP 36 DEBUG PRINT-OUT SLAB AND TIME-STEP :
C      IZPR1<1>,IZPR2<1>,ISTPR1<1>,ISTPR2<1>
C---------------------  ---------------  ---------------------
C---   GROUP 37 DEBUG SWEEP AND SUBROUTINES :
C      KENU,KMAIN,KINDEX,KGEON,KINPUT,KSODAT,KCOMPF,KSORCE,
C      KSOLV1,KSOLV2,KSOLV3,KCOMPP,KADJST,PFLUX,KSHIFT,KDIF,
C      KCOMPU,KCOMPV,KCOMPW,KCOMPR,KWALL,KDBRHO<-1>,KDBEXP,KDBNDT
C      KDBGEN
C---------------------  ---------------  ---------------------
C---   GROUP 38 MONITOR,TEST,AND FLAG :
C      MONITR<.F.>,FLAG<.F.>,TEST<.T.>,KFLAG<1>
C      END OF MAINTENANCE-ONLY SECTION
C---------------------  ---------------  ---------------------
C---   GROUP 39 ERROR AND RESIDUAL PRINT-OUT :
C      IERRP<1000>,RESREF(1,3-24)<25*1.>,RESMAP<.F.>,
C      RESID(1-25)<2*.F.,23*.T.>,KOUTPT
       RESREF(1)=WIN*AINLET*.01
C---------------------  ---------------  ---------------------
C---   GROUP 40 SPECIAL DATA : LOGIC(1..10),INTGR(1..10),RE(21..30)
C      NLSP<1>,NISP<1>,NRSP<1>,SPDATA<.F.>,LSPDA(1),ISPDA(1),RSPDA(1)
C      USE FIRST 10 ELEMENTS OF ARRAYS LOGIC & INTGR AND 21ST
C      TO 30TH OF ARRAY RE FOR TRANSFERRING SPECIAL DATA FROM
C      SATELLITE TO GROUND, BUT IF REQUIREMENTS EXCEED THIS
C      PROVISION SET SPDATA = .T., AND DIMENSION ARRAYS LSPDA,
C      ISPDA, RSPDA ABOVE AND IN GROUND AS NEEDED, AND SET HERE
C      NLSP, NISP, NRSP TO DIMENSION VALUES.
C---------------------  ---------------  ---------------------
C---   GROUP 42 RESTARTS AND DUMPS : SAVEM<.F.>,RESTRT<.F.>-KINPUT
       SAVEM=.TRUE.
       IF(FSWEEP.GT.1) RESTRT=.TRUE.
C---------------------  ---------------  ---------------------
       .
       .
       .
       .
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX USER SECTION 3 ENDS.
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX STANDARD SECTION 4 STARTS:
C-------------------------------------------------------------------
C  WRITE GENERAL DATA ON TO THE GUSIE1.DTA TAPE, ETC...
            IF(SPDATA) CALL WRTSPC(LSPDA,NLSP,ISPDA,NISP,RSPDA,NRSP)
            IF(BLOCK) CALL WRTPOR(PE,PN,PH,PC,NX,NY,NZ,IPLANE)
       IF(BFC) CALL WRTBFC(14,NBFC,XE,XW,YN,YS,ZH,ZL,
      &ND,NX+1,NY+1,NZ+1,NZ,PRTBFC)
C      OLD PRACTICES RETAINED FOR REFERENCE:
C           IF(SPDATA) CALL SPCDAT(IRUN)
C           IF(BLOCK) CALL PORDAT(IRUN)
            IF(GRAPHS) CALL SORT(IRUN)
            IF(RESTRT) GO TO 902
          DO 901 INDVAR=1,25
            IF(IFIX(FINIT(INDVAR)+0.1).NE.10101) GO TO 901
       WRITE(6,6742) FMUB,FMFB,HISAT
 6742  FORMAT(" FMUB BEFORE CALL FLDDAT",1P3E12.4)
       CALL FLDDAT(IRUN)
       GO TO 902
  901  CONTINUE
  902  CALL DATAIO(WRT,10)
            IF(MONITR) CALL DATAIO(WRT,-6)
  999  CONTINUE
       STOP
       END
```

```
      SUBROUTINE TEMPER(HSTAT,TO,T,CPDR,RGAS,SC,NSC)
C---------- SUBITERATIVE CALCULATION OF TEMPERATURE ----------
      DIMENSION SC(NSC)
      DATA NITER,DTO,TMIN/12,50.,100./
      DT=DTO
      TEMP=TO
      CALL ENTHAL(TEMP,HHH,CPDR,SC,NSC)
      ENTH=HHH*RGAS*TEMP
      IF(HSTAT.LT.ENTH) DT=-DT
      TEMPL=TEMP
C     WRITE(6,6505) TO,ENTH,HSTAT,RGAS,SC(1),SC(2),SC(3)
C6505 FORMAT(" TO E HS RG SC",1P7E12.4)
      TEMP =TEMP+DT
      ITER=0
   10 ENTHL=ENTH
      ITER=ITER+1
      CALL ENTHAL(TEMP,HHH,CPDR,SC,NSC)
      ENTH =HHH*RGAS*TEMP
      RENTH=(HSTAT-ENTHL)/((ENTH-ENTHL)+1.E-9)
C     WRITE(6,6500) ITER,TEMP,ENTH,ENTHL,HSTAT,RENTH
C6500 FORMAT(" IT T E EL HS RE",I2,1P5E12.4)
      IF(ABS(ENTH-ENTHL).LT..001*ABS(ENTH)) RENTH=1.
      TEMP1=TEMPL+(TEMP-TEMPL)*RENTH
      TEMP1=AMAX1(TEMP1,.5*TEMP,TMIN)
      TEMP1=AMIN1(TEMP1,1.5*TEMP,5000.)
      TEMPL=TEMP
      TEMP=TEMP1
      AR=ABS(RENTH)
      IF( (AR.GT.1.005 .OR. AR.LT..995) .AND. ITER.LT.NITER) GO TO 10
      T=TEMP
      RETURN
      END

      SUBROUTINE ENTHAL(TEMP,HSUM,CPSUM,SC,NSC)
      DIMENSION SC(NSC),ZS(7,2,8)
      DATA ZS/2.717,2.945E-3,-8.022E-7,1.023E-10,-4.847E-15,-2.991E4
     1 ,6.631,4.07,-1.108E-3,4.152E-6,-2.964E-9,8.07E-13
     2 ,-3.028E4,-3.227E-1
     3 ,3.1,5.112E-4,5.264E-8,-3.491E-11,3.695E-15,-8.774E2
     4 ,-1.963,3.057,2.667E-3,-5.81E-6,5.521E-9,-1.812E-12
     5 ,-9.889E2,-2.3
     6 ,3.622,7.362E-4,-1.965E-7,3.620E-11,-2.895E-15,-1.202E3
     7 ,3.615,3.626,-1.878E-3,7.055E-6,-6.764E-9,2.156E-12
     8 ,-1.048E3,4.305/
       NS=NSC
      IF(SC(3).LT..000001) NS=NSC-1
      K=1
      IF(TEMP.LT.1000.) K=2
      TEMP2=TEMP*TEMP
      HSUM=0.
      CPSUM=0.
      DO 6 IS=1,NS
      CP1=ZS(1,K,IS)
      CP2=ZS(2,K,IS)*TEMP
      CP3=ZS(3,K,IS)*TEMP2
      CP4=ZS(4,K,IS)*TEMP2*TEMP
      CP5=ZS(5,K,IS)*TEMP2*TEMP2
      CPSUM=CPSUM+SC(IS)*(CP1+CP2+CP3+CP4+CP5)
    6 HSUM =HSUM+
     1  SC(IS)*(CP1+.5*CP2+.33333*CP3+.25*CP4+.2*CP5+ZS(6,K,IS)/TEMP)
      RETURN
      END
```

```
      SUBROUTINE MSOLV(GA,KS,AAT,AM,S,TTT,PTP,RTR,VRT,ORT)
      DATA R/8305.6/
      G1=GA-1.
      G2=G1*.5
      G3=1./G1
      G4=GA/G1
      G5=GA+1.
      G6=G5/(2.*G1)
      NITER=0
      IF(KS.GT.0) GO TO 9
C---SUBSONIC--
      IF(AM.GT..9999)AM=0.
    1 AML=AM
      AM=((2.+G1*AM*AM)/G5)**G6/AAT
      NITER=NITER+1
      IF(NITER.GT.100) GO TO 99
      IF(ABS(AM-AML)/AM.LT..001) THEN
      S=AM*AM
      GO TO 10
      END IF
      GO TO 1
C----SUPERSONIC---
    9 G7=1/G6
      IF(AM.LT.1.0001) AM=1.0001
    2 S=((AAT*AM)**G7-2./G5)*G5/G1
      AML=AM
      AM=SQRT(S)
      NITER=NITER+1
      IF(NITER.GT.100) GO TO 99
      IF(ABS(AM-AML)/AM.LT..001) GO TO 10
      GO TO 2
   99 WRITE(6,999) AM,AML,AAT,KS
  999 FORMAT('   TOO MANY ITERATIONS  ',3E10.4,I4)
   10 TTT=1.+G2*S
      PTP=TTT**G4
      RTR=TTT**G3
      VRT=SQRT(GA*R/TTT)*AM
      ORT=SQRT(GA/R)*AM/TTT**G6
      RETURN
      END
```

```
      SUBROUTINE FLDDAT(IRUN)
C-----------------------------------------------------------------------
C     FIELDS IS USED TO SPECIFY NON-UNIFORM INITIAL FIELDS.
C     EARTH SETS UNIFORM INITIAL FIELDS TO FIINIT(MPHI), EXCEPT
C     WHEN FINIIT(MPHI)=10101.0 WHICH IS THE SIGNAL THAT EARTH
C     READS THE NON-UNIFORM FIELDS TAPE THE CONTENTS OF WHICH
C     ARE SET HERE.
C     IT IS ESSENTIAL TO PROVIDE SETTINGS FOR ALL THOSE MPHI'S
C     FOR WHICH FIINIT(MPHI) HAS BEEN SET TO 10101.THE SETTING
C     ORDER  M U S T  FOLLOW THE STANDARD ORDER OF BLOCK DATA.
C     NOTE: EARTH PRINTS OUT THE INITIAL FIELDS IF KOUTPT=-1.
C
C***  PLEASE NOTE THAT THE PHI ARRAY  M U S T  BE SET AS
C     PHI(IY,IX)=...,NOT AS PHI(IX,IY)=...
C     ALSO, YOU  M U S T  DIMENSION PHI TO THE MAXIMUM
C     DIMENSIONS USED IN THE RUNS DEFINED IN SATLIT, VIZ.
C     DIMENSION PHI(NY MAX.,NX MAX.)
C-----------------------------------------------------------------------
CHAPTER 1      PRELIMINARIES
C-----------------------------------------------------------------------
$INCLUDE 9,CMNBUSSI.FTN/G
$INCLUDE 9,BUSSEQUI.FTN/G
$INCLUDE 9,NOZBF1.FTN
C------ USER EQUIVALENCES-----------------
      EQUIVALENCE (FMFB,RE(4))
      DIMENSION PHI(20,1),FDTAPE(3)
      INTEGER FTAPE
      LOGICAL FIRST
      INTEGER P1,PP,U1,U2,V1,V2,W1,W2,R1,R2,RS,EP,H1,H2,H3,C1,C2,
     &C3,C4
      DATA P1,PP,U1,U2,V1,V2,W1,W2,R1,R2,RS,KE,EP,H1,H2,H3,C1,C2,
     &C3,C4/1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20/
      DATA FIRST,FTAPE,FDTAPE/.TRUE.,9,4HFIEL,4HDS.D,2HTA/
          IF(FIRST) CALL TAPES(FTAPE,FDTAPE,3,1,4*NX*NY)
      FIRST=.FALSE.
      THRTS=THROAT**2
C-----------------------------------------------------------------------
CHAPTER 2  USER CHAPTER FOR SETTING INITIAL FIELDS.
C-----------------------------------------------------------------------
      NNZ=NZ
          IF(PARAB) NNZ=1
        DO 2001 IZ=1,NNZ
        DO 2000 MPHI=1,25
          IF(MPHI.EQ.2) GO TO 2000
          IF(IFIX(FIINIT(MPHI)+0.1).NE.10101) GO TO 2000
          IF(.NOT.STOVAR(MPHI).AND.,NOT.SOLVAR(MPHI)) GO TO 2000
C************USER SECTION STARTS HERE************
C     FOR EACH VARIABLE, MVAR, FOR WHICH FIINIT(MVAR) IS SET TO
C     10101.0 IN BLOCK DATA, THE USER MUST INSERT HERE FORTRAN
C     STATEMENTS FOR SETTING HIS WANTED NON-UNIFORM INITIAL FIELD.
C     THE FORTRAN-STATEMENT MODEL TO BE FOLLOWED BY THE USER FOR
C     EACH MVAR IS AS FOLLOWS...
C
```

```
            IF(MPHI.NE.P1) GO TO 205
          AAT=YN(1,IZ+1,1)**2/THRTS
          KS=1
          IF(IZ.LT.NZT) KS=0
          CALL MSOLV(GA,KS,AAT,AM,S,TTT,PTP,RTR,VRT,ORT)
          PSTAT=PTOT/PTP
          TSTAT=TTOT/TTT
          WRITE(6,6782) IZ,AAT,AM,TTT,PTP,PSTAT,TSTAT,VRT*WFAC
 6782 FORMAT("MSOLV CALL IN FLDDAT IZ=",I2," AAT AM ",1P2E12.4,
     1 " TT PT P T W ",1P5E12.4)
            DO 201 IX=1,NX
            DO 201 IY=1,NY
  201 PHI(IY,IX)=PSTAT
          WRITE(FTAPE) ((PHI(IY,IX),IY=1,NY),IX=1,NX)
  205 CONTINUE
C
C       INSERT HERE ADDITIONAL FORTRAN SEQUENCES, SIMILAR TO THAT
C       GIVEN ABOVE, FOR EACH MVAR FOR WHICH FIINIT(MVAR)=10101.0
            IF(MPHI.NE.W1) GO TO 305
          WVEL=VRT*WFAC
            DO 301 IX=1,NX
            DO 301 IY=1,NY
  301 PHI(IY,IX)= WVEL
          WRITE(FTAPE) ((PHI(IY,IX),IY=1,NY),IX=1,NX)
  305 CONTINUE
            IF(MPHI.NE.H2) GO TO 405
            DO 401 IX=1,NX
            DO 401 IY=1,NY
  401 PHI(IY,IX)= TSTAT
          WRITE(FTAPE) ((PHI(IY,IX),IY=1,NY),IX=1,NX)
  405 CONTINUE
          IF(MPHI.NE.C1) GO TO 505
          COMP=FNFB
          IF(IZ.EQ.1) COMP=FMUB
          DO 501 IX=1,NX
          DO 501 IY=1,NY
  501 PHI(IY,IX)=COMP
          WRITE(FTAPE) ((PHI(IY,IX),IY=1,NY),IX=1,NX)
  505 CONTINUE
C************USER SECTION ENDS HERE  ************
 2000 CONTINUE
          WRITE(6,6791) IZ,TSTAT,PSTAT,WVEL,COMP
 6791 FORMAT(" IZ T P W MH2",I3,1P4E12.4)
 2001 CONTINUE
          RETURN
          END

C*DIRECTIVE**CMNBF1**
          COMMON/FOB/F1(5000)
          COMMON/CIB/ND/CIC/KOORD
          COMMON/CID/KDBGG,KDBGNF,KDBGCD,KDBIND,KDBNFX,KDBCDT,KDBFCS
          COMMON/CIE/KDBGS,KDBINS
          COMMON/CIF/IGEN
          COMMON/CRA/XW(21,42,1)/CRB/XE(21,42,1)
         &       /CRC/YS(2,42,1)/CRD/YN(2,42,1)
         &        /CRE/ZL(2,21,1)/CRF/ZH(2,21,1)
         &        /CRG/RCON/CRH/DARCY
          COMMON/CLA/STORSA(6),STORWD(6),STORP,STORPE,STORPN,
         &           STORPH,STOR1,STOR2,STOR3,PRTCON,PRTBFC,STOCRN
          COMMON/CLC/BFPLOT
          LOGICAL STORP,STORPE,STORPN,STORPH,STOR1,STOR2,STOR3,
         &        STORSA,STORWD,PRTCON,PRTBFC,BFPLOT,STOCRN
          COMMON/NOZ/WFAC,PTOT,TTOT,GA,NZT,THRDAT,FMUB
```

```
      SUBROUTINE GROUND(IRN,ICHAR,ISTP,ISNP,IZED,INDVAR)
$INCLUDE 9,CMNGUSSI.FTN/G
$INCLUDE 9,GUSSEQUI.FTN/G
C$INCLUDE 9:NMLIST.FTN/G
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX STANDARD SECTION 1 STARTS:
C     VARIABLE NAMES FOR USE IN GROUND:
      COMMON/TYPE/CELL,EAST,WEST,NORTH,SOUTH,HIGH,LOW,VOLUME,WALL
      COMMON/VAR/P1,PP,U1,U2,V1,V2,W1,W2,R1,R2,RS,
     &KE,EP,H1,H2,H3,C1,C2,C3,C4,RX,RY,RZ,S1,S2
      COMMON/VAROLD/P10,PP0,U10,U20,V10,V20,W10,W20,R10,R20,RS0,
     &KE0,EP0,H10,H20,H30,C10,C20,C30,C40,RX0,RY0,RZ0,S10,S20
      COMMON/VARLOW/P1L,PPL,U1L,U2L,V1L,V2L,W1L,W2L,R1L,R2L,RSL,
     &KEL,EPL,H1L,H2L,H3L,C1L,C2L,C3L,C4L,RXL,RYL,RZL,S1L,S2L
      COMMON/VARHI/P1H,PPH,U1H,U2H,V1H,V2H,W1H,W2H,R1H,R2H,RSH,
     &KEH,EPH,H1H,H2H,H3H,C1H,C2H,C3H,C4H,RXH,RYH,RZH,S1H,S2H
      COMMON/GMTRY/VOL,VOLO,AEAST,ANORTH,AHIGH,AEDX,ANDY,AHDZ
      COMMON/PROP/D1,D2,D1DP,D2DP,MU1,MU1LAM,EXCO,CFF,MDT,HST1,HST2
      COMMON/PRPOLD/D10,D20
      COMMON/PRPLOW/D1L,D2L,EXCOL
      COMMON/PRPHI/D1H,D2H,MU1H,EXCOH
      COMMON/VARNX/XG,XU,DXU,DXG
      COMMON/VARNY/YG,YV,DYV,DYG,R,RV
      COMMON/VARNZ/ZG,ZW1,DZW,DZG,WGRID
      COMMON/GDMSCI/XPLANE,YPLANE,ZPLANE,ITNO
      COMMON/GDMSCL/LSLAB,MSLAB,HSLAB,LAMMU
      REAL NORTH,LOW
      INTEGER     P1,PP,U1,U2,V1,V2,W1,W2,R1,R2,RS,
     &EP,H1,H2,H3,C1,C2,C3,C4,RX,RY,RZ,S1,S2
      INTEGER     P10,PP0,U10,U20,V10,V20,W10,W20,R10,R20,RS0,
     &EP0,H10,H20,H30,C10,C20,C30,C40,RX0,RY0,RZ0,S10,S20
      INTEGER     P1L,PPL,U1L,U2L,V1L,V2L,W1L,W2L,R1L,R2L,RSL,
     &EPL,H1L,H2L,H3L,C1L,C2L,C3L,C4L,RXL,RYL,RZL,S1L,S2L
      INTEGER     P1H,PPH,U1H,U2H,V1H,V2H,W1H,W2H,R1H,R2H,RSH,
     &EPH,H1H,H2H,H3H,C1H,C2H,C3H,C4H,RYH,RYH,RZH,S1H,S2H
      INTEGER VOL,VOLO,AEAST,ANORTH,AHIGH,AEDX,ANDY,AHDZ
      INTEGER D1,D1DP,D2,D2DP,EXCO,CFF,HST1,HST2
      INTEGER D10,D20,D1L,D2L,EXCOL,D1H,D2H,EXCOH
      INTEGER XG,XU,DXU,DXG,YG,YV,DYV,DYG,R,RV,ZG,ZW1,DZW,
     &DZG,WGRID
      INTEGER XPLANE,YPLANE,ZPLANE
      LOGICAL LSLAB,MSLAB,HSLAB,LAMMU,LSPDA
      EQUIVALENCE (M1,R1),(M2,R2)
C     SATLIT-EQUIVALENT IRUN:
      EQUIVALENCE (IRUN,INTGR(11))
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX STANDARD SECTION 1 ENDS.
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX USER SECTION 1 STARTS:
C     ARRAYS ( DIMENSIONED NY,NX ) FOR USE WITH 'ADD':
      DIMENSION CVAR(20,1),VVAR(20,1),CM(20,1),VM(20,1),ZERO(20,1)
C     SPECIAL-DATA ARRAYS DIMENSIONED & DIMENSION VALUES SET HERE:
      DIMENSION LSPDA(1),ISPDA(1),RSPDA(1)
C----- USER PLACES HIS VARIABLES, ARRAYS, EQUIVALENCES ETC. HERE.
      DIMENSION GV(20,1),GW(20,1),GP(20,1),GPIZ1(20,1),GRH(20,1),
     1 GTEMP(20,1),CFU(20,1),GZNODE(41),GTWALL(41),GCPNIX(20,1),
     2 GENTH(20,1),    GW1(20,1),GV1(20,1) ,SC(3)
      DIMENSION GAN(20,1),GAHT(20,1),GAH1(20,1),GAEX(20,1),GCPNW(41),
     1 GPNW(41),GPAX(41),GTNW(41),GTAX(41),GZW(41),GAMGWL(41),GYV(20)
     2 ,GWCAR(20,1),GWCARL(20,1),GVCAR(20,1),GARNWL(41),GHTCOE(41),
     3 GWMOL(20),GMACH(20,1)
C----- GEOMETRY DATA OF CELL VERTICES
      DIMENSION GXC(2,21),GYC(2,21),GZC(2,21),GZCELL(42),GYWALL(42),
     1 GDYNY(42)
```

```
C----USER EQUIVALENCES
      EQUIVALENCE (SC(1),RE(1)),(FMFB,RE(4))
      DATA NLSP,NISP,NRSP/1,1,1/
      DATA CVAR,VVAR,CM,VM,ZERO/100*0.0/
      DATA RGAS/8305.6/
      DATA ISWPF1,ISWFLA/1,3/
C     USER PLACES HIS DATA STATEMENTS HERE.
      DATA ARCF,CRCF,ARCR,CRCR/3.7656E7,800.,2.8283E2, 5644.0/
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX USER SECTION 1 ENDS.
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX STANDARD SECTION 2 STARTS:
C     PLEASE DO NOT ALTER, OR RE-SET, ANY OF THE REMAINING
C     STATEMENTS OF THIS SECTION.
          IF(SPDATA)
     &CALL RDSPC(IRN,INTGR(12),LSPDA,NLSP,ISPDA,NISP,RSPDA,NRSP)
      ZWTEMP=ZWDIST(31)
      ZWDIST(31)=0.
      CALL GRDUTY(IRN,ICHAP,IZED,INDVAR)
      ZWDIST(31)=ZWTEMP
      CALL BFCGRD(IRN,ICHAP,ISWP,IZED,INDVAR)
          IF(ICHAP.EQ.-5) GO TO 10
          IF(ICHAP.LE.0.OR.ICHAP.GT.16) RETURN
      GO TO (100,200,300,400,500,600,700,800,900,1000,1100,1200,
     &1300,1400,1500,1600),ICHAP
      RETURN
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX STANDARD SECTION 2 ENDS.
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX USER SECTION 2 STARTS:
C-------------------------------------------------------------------
C     CHAPTER 0: MODIFY SATLIT DATA, AT START OF EACH IRN.
C-------------------------------------------------------------------
C          IF(.NOT.NAMLST) RETURN
C          IF(IRN.EQ.NRUN) DATFIL=.FALSE.
C---  READ SATLIT DATA NAMELIST HERE
C     CALL WRIT40(40HENTER NAMELIST DATA FOR GROUPS 1 TO 24   )
C     READ(20,G1G24)
C     CALL WRIT40(40HENTER NAMELIST DATA FOR GROUPS 25 TO 42 )
C     READ(20,G25G42)
   10 CONTINUE
      GPI=4.*ATAN(1.)
C----- IN NOZSAT X-RANGE IS SET AS  = .01*2.RADIANS
      GPI100=GPI*100.
C----- OPEN BFCXYZ FILE TO READ GRID VERTICES --------------
      NXP1=NX+1
      NYP1=NY+1
      NZP1=NZ+1
      NXNY=NX*NY
      LREC=4*3*NXP1*NYP1
      OPEN(23,FILE="BFCXYZ",ACCESS="DIRECT",BLOCKSIZE=LREC+4,
     1 COUNTBY="RECORD",STATUS="OLD",RECL=LREC)
      WRITE(6,6541)
 6541 FORMAT("FILE BFCXYZ ON LU23 IS OPEN")
      ISKIPA=0
      ISKIPB=0
      CALL WALDP(-1,0,NZ,1,1.,1.,1.,1.,1.,1.,1.,1.,1.,1., VALUE,COEF)
      FMUB=(1.+8.*FMFB)/9.
      WRITE(6,6298) FMFB,FMUB,HISAT
 6298 FORMAT(" FMFB=",1PE12.4," FMUB ",1PE12.4," HIS",1PE12.4)
      RETURN
```

```
C-----------------------------------------------------------------------
C      CHAPTER 1: CALLED AT THE START OF EACH TIME STEP.
C      SET 'DT' HERE WHEN TLAST SET NEGATIVE IN BLOCK DATA.
C      'ATIME + DT' GIVES THE END TIME OF THE CURRENT TIME STEP
C      NOT ACCESSED IF STEADY,OR PARABOLIC.
C-----------------------------------------------------------------------
  100 CONTINUE
      RETURN
C-----------------------------------------------------------------------
C      CHAPTER 2: CALLED AT THE START OF EACH SWEEP.
C-----------------------------------------------------------------------
  200 CONTINUE
      IF(ISKIPA.GE.1) RETURN
      ISKIPA=ISKIPA+1
C----- PREPARE WALL TEMPERATURES
      NTHRO=6
      CALL GET1D(ZW1,GZNODE,NZ)
      ZTHRO=GZNODE(NTHRO)
      CALL GET1D(ZG,GZNODE,NZ)
      CALL TWALBC(NZ,GTWALL,GZNODE,ZTHRO)
      WRITE(6,3006) ISWP,ZTHRO
 3006 FORMAT("WALL TEMPERATURES SET IN CH 2 AT ISWEEP=",I4," ZT="
     1 1PE12.4)
C----- SETUP GEOMETRY CONSTANTS----------
      DO 3120 IZ=1,NZP1
      READ(23,REC=IZ  +1) ((GXC(IX,IY),IY=1,NYP1),IX=1,NXP1),
     1                    ((GYC(IX,IY),IY=1,NYP1),IX=1,NXP1),
     2                    ((GZC(IX,IY),IY=1,NYP1),IX=1,NXP1)
      WRITE(6,3008) (GYC(1,IY),IY=1,NY)
 3008 FORMAT(" GYC"/(1P10E12.4) )
      GZCELL(IZ)=GZC(1,1)
      GYWALL(IZ)=GYC(1,NYP1)
 3120 GDYNY (IZ)=.5*( GYC(1,NYP1)-GYC(1,NY) )
      THROAT=GYWALL(NTHRO)
      WRITE(6,3123) (GZCELL(IZ),IZ=1,NZ+1)
 3123 FORMAT("GZCELL "/(1P10E12.4) )
C----- CALCULATE WALL INCLINATION ANGLE ,
      DO 3140 IZ=1,NZ
 3140 GANGWL(IZ)=ATAN((GYWALL(IZ+1)-GYWALL(IZ))/
     1                (GZCELL(IZ+1)-GZCELL(IZ)) +1.E-9)
      WRITE(6,3144) (GANGWL(IZ),IZ=1,NZ)
 3144 FORMAT("WALL ANG"/(1P10E12.4))
      RETURN
C-----------------------------------------------------------------------
C      CHAPTER 3: CALLED AT THE START OF EACH SLAB:
C      NOT ACCESSED IF PARABOLIC, BUT 'STRIDE' IS.
C-----------------------------------------------------------------------
  300 CONTINUE
      IRELS=50
      IRELE=150
      GRELRA=FLOAT(ISWP-IRELS)/FLOAT(IRELE-IRELS)
      GRELRA=AMIN1(1.,AMAX1(0.,GRELRA))
      RLXP=.1+.4*GRELRA
      RLXPZ=RLXP
      RLXPXY=RLXP
      DTFALS(W1)=THROAT*(.001+100.*GRELRA)
      DTFALS(V1)=DTFALS(W1)
      RETURN
C-----------------------------------------------------------------------
C      CHAPTER 4: CALLED AT THE START OF EACH RE-CALCULATION OF
C      VARIABLES P1,...C4 AT CURRENT SLAB. ITNO= ITERATION NUMBER.
C-----------------------------------------------------------------------
  400 CONTINUE
      RETURN
```

```
C-----------------------------------------------------------------------
C      CHAPTER 5: GROUND CALLED WHEN SOURCE TERM IS COMPUTED.
C      INDVAR GIVES DEPENDENT VARIABLE IN QUESTION IE. U1,...,C4.
C      TO ADD SOURCE TO DEPENDENT VARIABLE C1(SAY) FOR IX=IXF,IXL
C      AND IY=IYF,IYL INSERT STATEMENT:
C      IF(INDVAR.EQ.C1)
C     &CALL ADD(INDVAR,IXF,IXL,IYF,IYL,TYPE,CM,VM,CVAR,VVAR,NY,NX)
C      NOTES ON 'ADD':
C     *SOURCE= (CVAR(IY,IX)+AMAX1(0.0,MASFLO))*(VVAR(IY,IX)-PHI),
C      WHERE 'PHI' IS IN-CELL VALUE OF VARIABLE IN QUESTION.
C     *'MASFLO'= CM(IY,IX)*(VM(IY,IX)-P),
C      WHERE 'P' IS THE IN-CELL PRESSURE.
C     *FOR INDVAR= M1, OR =M2, SOURCE ADDED IS 'MASFLO' ONLY,
C      EXCEPT FOR ONEPHS=.F. & MASFLO < 0.0 (IE. OUTFLOW) WHEN
C      CM(IY,IX) IS MULTIPLIED BY R1*D1 (FOR M1) & R2*D2 (FOR M2).
C     *BOTH 'CVAR' & 'CM' ARE MUTLIPLIED BY CELL-GEOMETRY QUANTITY
C      DICTATED BY SETTING OF 'TYPE' (=CELL, EAST AREA,..VOLUME).
C     *TYPE-SPECIFIED AREAS ARE CALCULATED AS IF BLOCKAGE ABSENT,
C      BUT 'VOLUME' WITH ACCOUNT FOR ITS PRESENCE.
C     *FOR ALL SOLVED VARIABLES, INCLUDING M1 ( & M2 WHEN ONEPHS=F),
C      IF 'CM'> 0.0 CALL 'ADD'; FOR M1 & M2 ALTHOUGH 'CVAR' & 'VVAR'
C      HAVE NO SIGNIFICANCE THEY MUST BE ENTERED AS ARGUMENTS.
C     *'CVAR', 'VVAR', 'CM' & 'VM' MUST BE DIMENSIONED NY,NX.
C-----------------------------------------------------------------------
  500 CONTINUE
C     WRITE(6,6789) ISWP,IZED,INDVAR
C6789 FORMAT(" IN CH 5 ISW IZ IV ",3I3)
      DO 502 IY=1,NY
      CVAR(IY,1)=0.
  502 VVAR(IY,1)=0.
      IF(INDVAR.NE.C1) GO TO 510
      CALL GET(C1,CFU,NY,NX)
      CALL GET(H2,GTEMP,NY,NX)
      CALL GET(D1,GRH,NY,NX)
      IX=1
      DO 508 IY=1,NY
C------ CHECK FUEL AND OXIDANT MASS FRACTION
      FUEL=AMAX1(FMFB, CFU(IY,IX) )
      FMOX=AMAX1(0.,8.*(CFU(IY,IX)-FMFB) )
      VVAR(IY,IX)=FMFB
      CVAR(IY,IX)=ARCF*EXP(-CRCF/GTEMP(IY,IX))*GRH(IY,IX)**2
     1 *CFU(IY,IX)*FMOX/(FUEL-FMFB+1.E-10)
C-----SOURCE TERMS FOR REVERSE REACTION
C     FMPR=1.-FMOX-CFU(IY,IX)
C     VVAR1(IY,IX)=FMUB
C     CVAR1(IY,IX)ARCR*EXP(-CRCR/GTEMP(IY,IX))*GRH(IY,IX)**2
C    1 *FMPR*FMPR/(FMUB-CFU(IY,IX)+1.E-10)
  508 CONTINUE
      CALL ADD(C1,1,NX,1,NY,VOLUME,CM,VM,CVAR,VVAR,NY,NX)
C     CALL ADD(C1,1,NX,1,NY,VOLUME,CM,VM,CVAR1,VVAR1,NY,NX)
      RETURN
```

```
C*****************  W A L L   F U N C T I O N S  ********************
  510 IF(IZED.EQ.NZ) GO TO 515
      IF(INDVAR.NE.H1) GO TO 517
C------ SAVE NEAR WALL DATA
  515 CALL GET(W1,GW1,NY,NX)
      IF(IZED.LT.NZ) GWFW1=GW1(NY,1)
      CALL GET(P1,GP,NY,NX)
      GWFP1=GP(NY,1)
      CALL GET(P1H,GP,NY,NX)
      GWFP1H=GP(NY,1)
      IF(IZED.EQ.NZ) GWFP1H=GWFP1
      CALL GET(D1,GRH,NY,NX)
      GWFD1=GRH(NY,1)
      CALL GET(D1H,GRH,NY,NX)
      GWFD1H=GRH(NY,1)
      IF(IZED.EQ.NZ) GWFD1H=GWFD1
      GPRL=SIGMA(24)
C
C     WRITE(6,6392) GWFP1,GWFP1H,GWFD1,GWFD1H,GWFW1
C6392 FORMAT(" P PH D DH W1  IN WALL",1P5E12.4)
  517 IF(INDVAR.NE.W1) GO TO 520
C------ WALL FUNCTIONS FOR W1
      GDZ=.5*(GZCELL(IZED+2)-GZCELL(IZED))
      CALL WALDP(IZED,ISWP,NZ,1,GDYNY(IZED),EMULAM,GWFD1,GWFD1H,GWFW1,
     1           1.,1.,GWFP1,GWFP1H,GDZ,VALUE,COEF)
      CVAR(NY,1)=COEF
      VVAR(NY,1)=0.
      CALL ADD(W1,1,NX,NY,NY,NORTH,CM,VM,CVAR,VVAR,NY,NX)
      RETURN
  520 IF(INDVAR.NE.H1) GO TO 530
C------ WALL FUNCTIONS FOR H1
      CALL GET(H1,GENTH,NY,NX)
      GDZ=GZCELL(IZED+1)-GZCELL(IZED)
      GDY=.5*(GDYNY(IZED)+GDYNY(IZED+1))
      CALL WALDP(IZED,ISWP,NZ,2,GDY,EMULAM,GWFD1,GWFD1H,GWFW1,
     1           GPRL,SIGMA(H1),GWFP1,GWFP1H,GDZ,VALUE,COEF)
      CVAR(NY,1)=COEF
      VVAR(NY,1)=GENTH(NY,1)+GCPNW(IZED)*(GTWALL(IZED)-GTNW(IZED))
      CALL ADD(H1,1,NX,NY,NY,NORTH,CM,VM,CVAR,VVAR,NY,NX)
C------ SAVE HEAT TRANSFER COEFF. FOR PRINTOUT
      IF(ISWP.EQ.LSWEEP) GHTCOE(IZED)=COEF
      RETURN
  530 IF(INDVAR.NE.KE) GO TO 540
C------ WALL FUNCTIONS FOR KE
      GDZ=GZCELL(IZED+1)-GZCELL(IZED)
      GDY=.5*(GDYNY(IZED)+GDYNY(IZED+1))
      CALL WALDP(IZED,ISWP,NZ,3,GDY,EMULAM,GWFD1,GWFD1H,GWFW1,
     I           GPRL,SIGMA(KE),GWFP1,GWFP1H,GDZ,VALUE,COEF)
      CVAR(NY,1)=COEF
      VVAR(NY,1)=VALUE
      CALL ADD(KE,1,NX,NY,NY,NORTH,CM,VM,CVAR,VVAR,NY,NX)
      RETURN
  540 IF(INDVAR.NE.EP) GO TO 550
      GDZ=GZCELL(IZED+1)-GZCELL(IZED)
      GDY=.5*(GDYNY(IZED)+GDYNY(IZED+1))
      CALL WALDP(IZED,ISWP,NZ,4,GDY,EMULAM,GWFD1,GWFD1H,GWFW1,
     1           GPRL,SIGMA(EP),GWFP1,GWFP1H,GDZ,VALUE,COEF)
      CVAR(NY,1)=COEF
      VVAR(NY,1)=VALUE
      CALL ADD(EP,1,NX,NY,NY,NORTH,CM,VM,CVAR,VVAR,NY,NX)
      RETURN
  550 CONTINUE
      RETURN
```

```
C-----------------------------------------------------------------------
C      CHAPTER 6: CALLED AT THE END OF EACH VARIABLE-RECALCULATION
C      CYCLE COMMENCED AT CHAPTER 4.  ITNO = ITERATION NUMBER.
C-----------------------------------------------------------------------
  600 CONTINUE
      RETURN
C-----------------------------------------------------------------------
C      CHAPTER 7: CALLED AT END OF EACH SLAB-WISE CALCULATION.
C-----------------------------------------------------------------------
  700 CONTINUE
C------ CALCULATION OF AUXILIARY VARIABLES ------------------
      IF(ISWP.NE.LSWEEP) RETURN
      CALL GET(16,GV1,NY,NX)
      CALL GET(21,GW1,NY,NX)
      CALL GET(P1,GP,NY,NX)
      IF(IZED.EQ.1) CALL GET(P1,GPIZ1,NY,NX)
      CALL GET(H2,GTEMP,NY,NX)
      CALL GET(D1,GRH,NY,NX)
      CALL GET1D(ZW1,GZW,NZ)
      CALL GRED1(32,IZED,GAN,NY,NX)
      GARNWL(IZED)=GAN(NY,1)
      IF(IZED.EQ.1     ) CALL GET( AHIGH,GAH1,NY,NX)
      IF(IZED.EQ.NTHRO) CALL GRED1(34,IZED,GAHT  ,NY,NX)
      IF(IZED.EQ.NZ-1  ) CALL GRED1(34,IZED,GAEX  ,NY,NX)
      IF(IZED.NE.NTHRO) GO TO 745
      GATT=0.
      GFLXT=0.
      DO 740 IY=1,NY
      GATT=GATT+GAHT(IY,1)*GPI100
      GFLXT=GFLXT+GRH(IY,1)*GAHT(IY,1)*GW1(IY,1)*GPI100
  740 CONTINUE
  745 IF(IZED.NE.NZ-1) GO TO 749
      GAEXT=0.
      GFLXE=0.
      DO 746 IY=1,NY
      GAEXT=GAEXT+GAEX(IY,1)*GPI100
      GFLXE=GFLXE+GRH(IY,IX)*GAEX(IY,IX)*GW1(IY,1)*GPI100
  746 CONTINUE
  749 CONTINUE
      IF(IZED.LT.NZ) RETURN
      WRITE(6,6671)
 6671 FORMAT(//" ******************* OUTPUT SUMMARY ****************"/")
      GPANEG=0.
      GPAPOS=0.
      GPAINJ=0.
      DO 772 IZ=1,NTHRO
  772 GPANEG=GPANEG+GPNW(IZ)*GARNWL(IZ)*SIN(GANGWL(IZ))*GPI100
      DO 773 IZ=NTHRO+1,NZ-1
  773 GPAPOS=GPAPOS+GPNW(IZ)*GARNWL(IZ)*SIN(GANGWL(IZ))*GPI100
      DO 774 IY=1,NY
  774 GPAINJ=GPAINJ+GPIZ1(IY,1)*GAH1(IY,1)*GPI100
      THRUST=GPAPOS+GPANEG+GPAINJ
      GIMPLS=THRUST/(GFLXT*9.81)
      WRITE(6,6761) GATT,GAEXT,GPAPOS,GPANEG,GPAINJ,GFLXT,GFLXE,
     1 THRUST,GIMPLS
 6761 FORMAT("THROAT AREA .  ",1PE12.4,/"EXIT   AREA    ",1PE12.4,/
     1 "PRES FORCE += ",1PE12.4/"PRES FORCE -= ",1PE12.4/
     1 "PRES FORCE ON INJ=",1PE12.4/"M FLUX THROUGH THROAT",1PE12.4/
     2 "M FLUX THROUGH EXIT  ",1PE12.4/"THRUST                ",1PE12.4,.
     3 /,"SPEC IMPULE IN SEC",1PE12.4)
```

```
      CALL GET1D(ZG,GZNODE,NZ)
      WRITE(6,6773)
 6773 FORMAT("IZ      ZG            ZND           YN          ANG",9X,
     1 "PW          PAX         TW              TNY            TAX")
      DO 777 IZ=1,NZ
      WRITE(6,6774) IZ,.5*(GZCELL(IZ)+GZCELL(IZ+1)),GZNODE(IZ),
     1 GYWALL(IZ),GANGWL(IZ)*GPI/180.,GPNW(IZ),GPAX(IZ),
     2 GTWALL(IZ),GTNW(IZ),GTAX(IZ)
 777  CONTINUE
 6774 FORMAT(I3,1P10E12.4)
      WRITE(6,6775)
 6775 FORMAT(/"OUTPUT SUMMARY IN BRITISH UNITS "/" IZ",5X,"ZG:TH",8X,
     1 "YN",7X,"PW(PSI)      PAX(PSI)      TW(R)      TNY(R)      TAX(R)")
      GPSI=6894.757
      DO 778 IZ=1,NZ
 778  WRITE(6,6777) IZ,GZNODE(IZ),GYWALL(IZ),GPNW(IZ)/GPSI,
     1 GPAX(IZ)/GPSI,GTWALL(IZ)*1.8,GTNW(IZ)*1.8,GTAX(IZ)*1.8
 6777 FORMAT(I3,1P10E12.4)
C----- PRINT HEAT THANSFER COEF
      WRITE(6,6801)
 6801 FORMAT(/"HEAT TRANSFER TO THE WALL INFORMATION PRINTOUT"/
     1 " IZ       ZND       COEF        COWF*AR             QDOT")
      DO 779 IZ=1,NZ
      GARHT=GHTCOE(IZ)*GARNWL(IZ)*GPI100
  779 WRITE(6,6792) IZ,GZNODE(IZ),GHTCOE(IZ),GARHT,
     1 GARHT*(GTWALL(IZ)-GTNW(IZ))
 6792 FORMAT(I3,1P7E12.4)
      RETURN
C-------------------------------------------------------------------------
C     CHAPTER 8: CALLED AT THE END OF EACH SWEEP:
C     NOT ACCESSED IF PARABOLIC.
C-------------------------------------------------------------------------
  800 CONTINUE
      RETURN
C-------------------------------------------------------------------------
C     CHAPTER 9: CALLED AT THE END OF EACH TIME STEP:
C     NOT ACCESSED IF PARABOLIC.
C-------------------------------------------------------------------------
  900 CONTINUE
      RETURN
```

```
C-----------------------------------------------------------------------
C      CHAPTER 10: SET PHASE 1 DENSITY HERE WHEN IRHO1=-1 IN DATA.
C      SET CURRENT-Z 'SLAB' DENSITY, D1, IF MSLAB=.T.,
C      EG.  IF(MSLAB) CALL SET(D1,1,NX,1,NY,GD1,NY,NX).
C      SET NEXT LARGER-Z 'SLAB' DENSITY, D1H, IF HSLAB=.T. & PARAB=F
C      EG.  IF(HSLAB) CALL SET(D1H,1,NX,1,NY,GD1H,NY,NX).
C      SET D(LN(D1))/DP (IE, D1DP) FOR UNSTEADY FLOW.
C      EG.  IF(MSLAB) CALL SET(D1DP,1,NX,1,NY,GD1DP,NY,NX).
C-----------------------------------------------------------------------
 1000 CONTINUE
C------ DENSITY IS CALCULATED FROM EQ OF STATE AS RO=P*W/(R*T)
      CALL GET(V1,GV,NY,NX)
      IF(IZED.LT.NZ) CALL GET(W1,GW,NY,NX)
      CALL GET(P1,GP,NY,NX)
      CALL GET(C1,CFU,NY,NX)
      CALL GET(H1,GENTH,NY,NX)
      CALL GET(H2,GTEMP,NY,NX)
      CALL GET(D1,GRH,NY,NX)
      WTMOL=14.0685
      IX=1
      DO 1010 IY=1,NY
      IF(SOLVAR(C1)) THEN
      FMOX=8.*(CFU(IY,IX)-FMFB)
      SC(1)=(1.-FMOX-CFU(IY,IX))/18.
      SC(2)=CFU(IY,IX)*.5
      SC(3)=FMOX/32.
      WTMOL=(SC(1)*18.+SC(2)*2.+SC(3)*32.)/(SC(1)+SC(2)+SC(3))
      END IF
      GWMOL(IY)=WTMOL
      ISUB=0
      IF(IY.EQ.NY) ISUB=1
      GEKIN=.5*(GW(IY,IX)*GW(IY,IX)+GV(IY-ISUB,IX)*GV(IY-ISUB,IX))
      GHSTAT=H1SAT-GEKIN
      IF(SOLVAR(H1)) GHSTAT=GENTH(IY,IX)-GEKIN
      CALL TEMPER(GHSTAT,GTEMP(IY,IX),GT,GCPDR,RGAS,SC,3)
      GRH(IY,IX)=GP(IY,IX)*WTMOL/(RGAS*GT)
      GTEMP(IY,IX)=GT
 1010 GCPMIX(IY,IX)=GCPDR*RGAS
      CALL SET(2,1,NX,1,NY,GRH,NY,NX)
      CALL SET(H2,1,NX,1,NY,GTEMP,NY,NX)
C--SAVE TEMPERATURES AND PRESSURES, AND ALCULATE MACH NO AT LAST SWEEP
      GTNW (IZED)=GTEMP (NY,1)
      GTAX (IZED)=GTEMP (1 ,1)
      GCPNW(IZED)=GCPMIX(NY,1)
      GPNW (IZED)=GP    (NY,1)
      GPAX (IZED)=GP    (1 ,1)
      IF(ISWP.LT.LSWEEP-1) RETURN
      CALL GET(W2,GWCAR,NY,NX)
      IF(IZED.LT.NZ) CALL GET(W2L,GWCARL,NY,NX)
      CALL GET(V2,GVCAR,NY,NX)
      ISUB=0
      DO 1050 IY=1,NY
      GWH=GWCAR(IY,1)
      IF(IZED.EQ.NZ) GWH=GWCARL(IY,1)
      GWL=GWCARL(IY,1)
      IF(IZED.EQ.1) GWL=GWCAR(IY,1)
      GWAV=.5*(GWL+GWH)
      GVAV=.5*(GVCAR(IY,1)+GVCAR(IY-ISUB,1))
      GSOUND=SQRT( 1.3 *8305. *GTEMP(IY,1)/GWMOL(IY) )
      GMACH(IY,1)=SQRT(GWAV**2+GVAV**2)/GSOUND
 1050 ISUB=1
      CALL SET(C2,1,NX,1,NY,GMACH,NY,NX)
      RETURN
```

```
      SUBROUTINE TWALBC(NZ,TWALL,ZNOD,ZTHRO)
      DIMENSION TWALL(NZ),ZNOD(NZ)
      COMMON/MY/ ZTOWD(27),ZTOW(27),TOW(27)
C------ ZTRO AND TOW DATA
      DATA NTOW/27/
      DATA ZTOWD/-2.4942,-2.1348,-1.9407,-1.7467,-.9704,-.7763,-.3881,
     1 -.1941,.1941,.3881,.9704,1.5526,1.9407,1.9601,3.8815,5.8222,
     1 6.7926,7.7629,8.7333,9.7037,11.6444,13.5851,15.5258,17.4666,
     1 19.4073,21.3480,23.5231/
      DATA TOW/1360.,1500.,1510.,1500.,1470.,1470.,1490.,1490.,840.,
     1 830.,820.,790.,760.,1450.,1260.,1060.,960.,890.,850.,830.,
     1 795.,765.,745.,730.,720.,715.,710. /
C------ SORT TWALL FROM INPUT ZTOW AND TOW ARRAYS SET AS DATA ABOVE
      DO 510 IPP=1,NTOW
  510 ZTOW(IPP)=ZTOWD(IPP)+ZTHRO
      WRITE(6,6781) (ZTOW(IPP),IPP=1,NTOW)
 6781 FORMAT("ZTOW "/(1P5E12.4))
      ZNODE=ZNOD(1)
      DO 512 IP1=1,NTOW
      IF(ZNODE.LT.ZTOW(IP1)) GO TO 514
  512 CONTINUE
  514 IPL=IP1
      IPLM=MAX0(IPL-1,1)
      TWALL(1)=TOW(IPL)+(ZTOW(IPL)-ZNODE)/(ZTOW(IPL)-ZTOW(IPLM)+
     1          1.E-10) *(TOW(IPLM)-TOW(IPL))
      DO 516 IZ1=2,NZ
      IF(ZNOD(IZ1).GT.ZTOW(IPL)) GO TO 517
  516 TWALL(IZ1)=TOW(IPL)+(ZTOW(IPL)-ZNOD(IZ1))/(ZTOW(IPL)-ZTOW(IPLM)+
     1          1.E-10)*(TOW(IPLM)-TOW(IPL))
  517 IZ=IZ1-1
      IPP=IPL
  520 IZ=IZ+1
      IF(IZ.GT.NZ) GO TO 530
      ZNODE=ZNOD(IZ)
      IF(ZNODE.GE.ZTOW(NTOW)) GO TO 526
      DO 522 IPP=IPP,NTOW
      IIIP1=MINO(IPP+1,NTOW)
      IF(ZNODE.GE.ZTOW(IPP).AND.ZNODE.LT.ZTOW(IIIP1))GO TO 524
  522 CONTINUE
  524 IPP=MINO(IPP,NTOW)
      IPPP=MINO(IPP+1,NTOW)
      TWALL(IZ)=TOW(IPPP)+(ZTOW(IPPP)-ZNODE)/(ZTOW(IPPP)-ZTOW(IPP)+
     1          1.E-10) *(TOW(IPP)-TOW(IPPP))
      GO TO 520
  526 TWALL(IZ)=TOW(NTOW)
      GO TO 520
  530 CONTINUE
      DO 5555 IZ=1,NZ
      WRITE(6,6784) IZ,ZNOD(IZ),TWALL(IZ)
 5555 CONTINUE
 6784 FORMAT(" IZ Z ",I3,1PE12.4," TWALL=",1PE12.4)
      RETURN
      END
```

```
      SUBROUTINE WALDF(IZ,ISMP,NZ,MPHI,DY,AMU,RHO,RHOH,W,PRL,PR,P,PH,
     1                 DZ,VALUE,COEF)
C-----------------------------------------------------------------------
C THIS SUBROUTINE CALCULATES THE WALL FUNCTIONS FOR FLOWS WITH SIGNI--
C FICANT AXIAL PRESSURE GRADIENTS, FOR REFERENCE SEE: T CEBECI AND
C A.M.O. SMITH "A FINITE ...",ASME J. BAS. ENG.,1970,P 523, ALSO SEE
C LAUNDER-SPALDING "MATHEMATICAL MODELS OF TURBULENCE", AP 1972.
C-----------------------------------------------------------------------
      DIMENSION SYPL(5),SUPL(5),SS(5)
      DATA NITR,CAP,TAUDK,TKMAX,TKMIN/5, .4 , .3 , 1.E5 , 1.E-5 /
      DATA MW1,MN1,MKE,MEP/1,2,3,4/
C-----  FIRST ENTRY WITH IZ=-1 TO SETUP CONSTANTS
      IF(IZ.GE.0) GO TO 100
      D116=11.6**3
      RCAP=1./CAP
      WALCON=.3*SQRT(.3)/CAP
      AA=1.+1./7.
      AC=(1./8.74)**(2./AA)
      BC=(1.-1./7.)/(1.+1./7.)
      CC=4.-ALOG(4.)
      CAP2=CAP**2
      IZL=0
      RETURN
C-----  NEW SLAB ENTERED SAVE SELECTED VARIABLES
  100 IF(IZ.EQ.IZL) GO TO 110
      IF(IZ.EQ.1) WL=W
      IF(IZ.EQ.1) PL=P
      WAV=.5*(W+WL)
      DPDZW=(PH-P )/DZ
      DPDZG=(PH-PL)/(2.*DZ)
      IF(IZ.EQ.NZ) DPDZG=(P-PL)/DZ
      PL=P
      WL=W
      IZL=IZ
  110 CONTINUE
C-----  STAGGERING
      IF(MPHI.NE.MW1) GO TO 120
      PRT=1.
      PRL=1.
      PFUN=1.
      WP=W
      RHOP=.5*(RHO+RHOH)
      DPDZP=DPDZW
      GO TO 121
  120 WP=WAV
      RHOP=RHO
      DPDZP=DPDZG
      PFUN=9.*(PRL/PRT -1.)*(PRT/PRL)**.25
      PFUN=PRL*.6666667
  121 PPC=ABS(DPDZP)*AMU/( (WP*RHOP)**2 *WP )
      RE=RHOP*DY*WP/AMU
```

```
      IF(MPHI.NE.MW1 .AND. MPHI.NE.MH1) GO TO 300
C----- WALL FUNCTIONS FOR W1 AND H1
      PPL=PPC*0116
      S0 =SQRT(1.+PPL*11.6)
      ARG=11.6*CAP-2.*(S0-1.)
      IF(ABS(ARG).LT.50.) GO TO 125
          WRITE(6,601) IZ,MPHI,ARG
  601     FORMAT("IZ MPHI ",2I3," BAD ARG IN CALC E WALL",1PE12.4)
          ARG=AMIN1(50.,AMAX1(-50.,ARG) )
  125 E=(2.+PPL*11.6+2.*S0) * EXP(ARG) *.25/11.6
      E=AMAX1(8.,E)
C----- ITERATIVE U+  Y+  CALCULATION  (U+ GUESS=25 ????????)
      VALUE=0.
      CF=AMU/(PPUN*DY)
      S=AC*AMAX1(RE,1.)**(BC-1.)
      IF(RE.LT.132.25) GO TO 212
      DO 210 ITR=1,NITR
      S0=1.+SQRT(1.+PPC*RE/S)
      SH=SQRT(S)
      S=CAP2/(ALOG(1.+E*RE*SH)-CC+2.*(S0-ALOG(S0)))**2
      S=AMAX1(1.E-10,S)
  210 CONTINUE
      CF=CF*RE*S
  212 COEF=CF*(1.+PPC*RE/S )
      RETURN
C----- WALL FUNCTIONS FOR TKE
  300 IF(MPHI.NE.MKE) GO TO 400
      PPL=PPC*0116
      S0 =SQRT(1.+PPL*11.6)
      ARG=11.6*CAP-2.*(S0-1.)
      IF(ABS(ARG).LT.50.) GO TO 305
          WRITE(6,602) IZ,MPHI,ARG
  602     FORMAT("IZ MPHI ",2I3," BAD ARG IN CALC E WALL",1PE12.4)
          ARG=AMIN1(50.,AMAX1(-50.,ARG) )
  305 E=(2.+PPL*11.6+2.*S0) * EXP(ARG) *.25/11.6
      E=AMAX1(8.,E)
C----- ITERATIVE U+  Y+  CALCULATION  (U+ GUESS=25 ????????)
      S=AC*AMAX1(RE,1.)**(BC-1.)
      DO 310 ITR=1,NITR
      S0=1.+SQRT(1.+PPC*RE/S)
      SH=SQRT(S)
      S=CAP2/(ALOG(1.+E*RE*SH)-CC+2.*(S0-ALOG(S0)))**2
      S=AMAX1(1.E-10,S)
  310 CONTINUE
      TAU=S*RHOP*WP**2
      TKFIX=AMAX1(TKMIN, TAU/(RHOP*TAUDK) )
      TKFIX=AMIN1(TKMAX, TKFIX)
      VALUE=TKFIX
      COEF =1.E10
      RETURN
C----- WALL FUNCTION FOR ED
  400 VALUE=WALCON*TKFIX*SQRT(TKFIX) /DY
      COEF=1.E10
      RETURN
      END
```